Application of Multiuser Detection to IS-95 Reverse Link

by

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Certificate

This is to certify that the work contained in the thesis entitled "*Application of Multiuser Detection to IS-95 Reverse Link*", by *Vishwanath S. Kambalyal*, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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Abstract

In Direct-Sequence Code Division Multiple Access (DS-CDMA) systems, conventional detection uses the matched filter and the desired user's spreading sequence. It does not exploit the structure of Multiple Access Interference (MAI). This results in sub-optimal performance. Iterative techniques like Serial and Partial Parallel Interference Cancellation in Multiuser Ddetection (MUD) have been widely studied for short spreading sequences. However, recently interest has been generated in long spreading sequences. In this thesis simulation studies have been done for different iterative techniques for MUD in the existing long code based second generation (2G) IS-95 mobile communication standard. The channel environments considered are MAI, Gaussian and Rayleigh. Two new algorithms with better performance have been proposed. Effect of near-far problem on MUD performance has also been studied.

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There are so many people I want to thank, for without their help I would have never made it this far. These people are largely responsible for much of the enjoyment and success I have experienced over the last one and half years of my life at IIT Kanpur, I am a little bit sad to see it end.

More than anything else, I thank my family for their unconditional love, which made this work possible. First of all I would like to thank my mom and dad for their faith in me in completing this program and mainly persuading me to join this program. My wife Roopa and daughter Ruchika are responsible for me not delaying completion of this dissertation any further.

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Chapter 1

Introduction

The last decade has witnessed a dramatic expansion of wireless technology for fulfilling increasing demand for mobile communications. With the available frequency resources being limited, there is a demand for increasing the capacity of the mobile communications in the available bandwidth itself. Coupled with this the demand for providing media rich services on the wireless medium has spawned tremendous research activity for capacity enhancement in the existing framework. The Third Generation (3G) wireless networks will begin operation very shortly. These wireless systems will be required to offer high data rates, enabling them to integrate voice communications with a wide range of multimedia applications over and above the normal features offered by the Second Generation (2G) Systems.

Thus the basic services required to be provided are

1) Voice/digital audio;

2) High speed data transmission;

3) Video conferencing and multimedia applications.

In addition requirement is also there for providing

1) Moving and live Video;

2) Internet browsing with facility for large data download etc..

The definition of 3G mobile radio systems is proceeding very fast in different parts of the world. Europe will have a family of standards incorporating Wideband-Code Division Multiple Access (W-CDMA) and Time Division-Code Division Multiple Access (TD-CDMA) and which will be refined over the next two years. Thus the preferred standard for provid-

ing wireless communication is the CDMA technique. This chapter provides a qualitative coverage, highlighting the subject matters that are pertinent to the thesis. The approach is to construct the complete picture in this opening chapter leaving details to the subsequent chapters that follow.

1.1 Background

The CDMA technique is based on the spread spectrum communication technique. The spread spectrum modulation and demodulation technique employs a transmission bandwidth that is much greater than the minimum bandwidth required to transmit the digital information. This is achieved by using distinct spreading sequences of large bandwidth for each user. In CDMA, allocated bandwidth is utilised simultaneously by all the users. The main advantage of CDMA over other multiaccess techniques is of providing high capacity. The other advantages are ability of exploiting voice activity, privacy, soft-capacity limit, soft hand-off capability. All these technological merits have made the CDMA as the air-interface technology for the next generation cellular services. CDMA can be achieved by two spreading schemes, Direct Sequence (DS-CDMA) and Frequency Hopping (FH-CDMA). In Direct Sequence each user is assigned a unique code sequence upon which the data sequence to be transmitted is modulated. In Frequency hopping each user transmits data on a narrow-band frequency slot, which changes according to a preassigned pattern, unique to each user.

The DS-CDMA system can be classified into two distinct classes-short code and long codes on the basis of the spreading sequence utilized for the spreading of the data signal. A practical digital wireless communication standard IS-95 [3] utilizes the long code as the spreading sequence in both the uplink and downlink.

The exponential growth of CDMA digital cellular subscribers, in addition to the seemingly insatiable demand for access to bandwidth intensive applications and its penetration into the wireless market, has led to a dramatic increase in research in the area of improving the quality and efficiency of CDMA digital cellular communication systems. Unlike a copper or fiber based communication system where additional bandwidth can be added to existing systems by upgrading or installing additional cables, wireless and cellular communications systems

have a fixed, finite amount of available bandwidth from which they have to serve their growing and increasingly sophisticated subscriber base. Coupled with the increasing performance of microprocessors and other integrated circuits, the three most promising technologies that will enable cellular systems to meet the future demands of subscribers currently are:

- Multiuser Detection,
- Spatial Diversity and
- Source and channel coding;

Research is going on in all the above three fields. However to enhance the existing systems capacity multiuser detection is the technique that can be used with minimal changes. In this thesis different Multiuser Detector (MUD) methods have been employed in the DS-CDMA environment as existing in the IS-95 2G mobile communication standard.

1.2 Single User Detection

In a mobile communication system multiple access to the common channel resources is vital. By selecting mutually orthogonal codes for all users, multiple-access interference-free single-user performance can be achieved. It is however not possible to maintain orthogonality between spreading codes in a mobile environment and thus multiple access interference (MAI) arises. The conventional detector used in the DS-CDMA system for detecting the signals is the matched filter based single-user detector. In this receiver desired user is detected by correlation of the locally generated spreading sequence to the received data signal. This matched filter detection treats the other user signals interference as an Additive White Gaussian Noise (AWGN) and tries to match the receiver to the gaussian noise channel. Thus conventional single-user detection techniques are severely affected by MAI, making such systems interference limited [14].

In the existing systems like IS-95, matched filter receiver ignores the existence of other users and tries to maximize its performance by strict power control while using RAKE receiver for combining multipaths. Thus when the number of active users increases or when some users signals become extremely strong (near-far effect), it is likely that weak users may

experience overwhelming MAI. However, this problem is not an inherent weakness of CDMA systems but due to single-user detection adopted in the system which is unable to exploit the structure of the MAI.

1.3 Multiuser Detection

More advnaced detection strategies can be used to improve performance and significant improvement can be obtained with a multiuser receiver. Multiuser receivers which utilize the structure of multi-access interference in order to improve performance among users have gained importance as they perform better than the matched filter receiver. This exploitation of the MAI results in lower BER coupled with more users in the system i.e. higher capacity for the system.

Verdu's seminal work [4] shows that an optimum detector which jointly detects all signals can significantly eliminate MAI, to provide a substantial increase in system capacity. However due to the complexity of the optimum receiver($O(2^{no.\ of\ users})$) it has not been possible to apply it in practical systems resulting in research in the suboptimal detectors which provide appreciable increase in capacity at reduced complexity in comparison to optimum detector.

Multiuser detector typically requires the knowledge of the codes and channels of all the users. In order to provide high fidelity detection it is necessary either implicitly or explicitly to characterize the wireless propagation channels. The channels are in general estimated with the use of training sequences or pilot symbols, which however reduces the spectral efficiency. Blind approaches, which estimate the channel without the use of training, have been proposed as a way to alleviate this problem and therefore are of great interest.

1.4 Motivation

Verdu's seminal work [4] paved the way for intense research activity in multiuser detector's in late 90's. However the main focus then was on reducing the complexity of the detector and the use was limited to short spreading code case. In the short code spreading system the spreading sequence utilized to spread the signal repeats every symbol interval. This

results in interference which is stationary at the symbol interval. In the case of long code spreading sequences only a short portion of the total signal period is utilized to spread the symbol. Hence, different symbols are spread by different portions of the spreading sequence which gives interference which is different from the case of short spreading sequences. The statistical properties of each portion of the long code resemble those of randomly selected sequences and hence they are also referred to as random-code CDMA [20]. Due to its highly intractable nature very little work has been done in the long spreading code case though the existing mobile system IS-95 is based on long spreading sequence both in uplink as well as in downlink. Recently some algorithms have been proposed for long code spreading sequence case but the DS-CDMA system considered for their implementation has been BPSK/QPSK modulation system. In this thesis the practical IS-95 standard has been taken which in the reverse link uses many of the interference containing techniques like orthogonal walsh modulation, data burst randomizer etc..

The motivation for the present work was to investigate the existing long code multiuser algorithms in a practical system such as IS-95 for different channel conditions. We wish to examine the techniques and suggest appropriate modifications so that capacity can be enhanced as compared to matched filter detection. The other relevent criteria which we wish to discuss are : complexity, time delay and near-far effect. It is expected that multiuser detection schemes would perform better even in near-far scenario i.e. when power control is not used. In this thesis only DS-CDMA is used though FH-CDMA is also being studied for multirate communications. Reverse link has been used as the capacity of the mobile communication systems is normally constrained by the reverse link capacity as the transmission in reverse link is normallly non-coherent and asynchronous and Pilot channel is normally not available.

1.5 Outline

The thesis is organised as follows. Chapter 2 gives a detailed introduction to multiuser detection and its different implementations, the transmitting and receiving model have been described. Chapter 3 contains detailed information regarding the algorithms employed for multiuser detection methods used in this thesis alongwith their relative merits and demerits.

Results and simulation curves are discussed in detail in Chapter 4. Conclusions are drawn and future trends in research have been given in the last Chapter.

Chapter 2

Introduction to Multiuser Detection

Multiuser detection refers to a class of algorithms in a multi-access communication system that "exploits the considerable structure of the multiuser interference in order to increase the efficiency with which channel resources are employed" [5]. Prior to 1986, the conventional wisdom among researchers in CDMA cellular communication systems was that the multiuser interference observed in each user's received signal was well modeled by a Gaussian random process and that matched filter detection, which ignored the structure of the interference, was nearly optimum in this case. Verdu's seminal work [4] shows that an optimum detector (in the sense of minimum bit error rate) which jointly detects all signals can significantly eliminate the MAI, to provide a substantial increase in system capacity. However this improved performance with respect to the matched filter detector came at an equivalent dramatic increase in complexity. This chapter explains the basic concepts of multiuser detection and different techniques for their implemenation. Excellent review papers of multiuser detection techniques are available [9],[14]. However, these papers focus on short spreading sequences, though the techniques can also be applied to long spreading sequences. A good introduction to CDMA cellular communication systems is [2] and a book for multiuser detection for CDMA communications is [5]. The outline of this chapter is as follows.

The transmitter, receiver and channel models for a multiuser CDMA communication system are described in section 2.1. These form a mathematical framework for understanding the different multiuser detection techniques. The conventional single user detector is explained in section 2.2, while necessity and advantages of multiuser detection are explained in

section 2.3 followed by the optimal detector in section 2.4. Next section 2.5 describes main multiuser detection techniques specifically for uplink (Mobile to Base Station) environment highlighting their advantages and disadvantages.

2.1 Model

In this section, model of a DS-CDMA system has been explained. In a DS-CDMA system data which can be a plain data sequence or some modulated sequence is first modulated by a wideband spreading signal followed by a second modulation using the carrier. The spreading signal is independent of the data signal. Fig. 2.1 illustrates a typical baseband

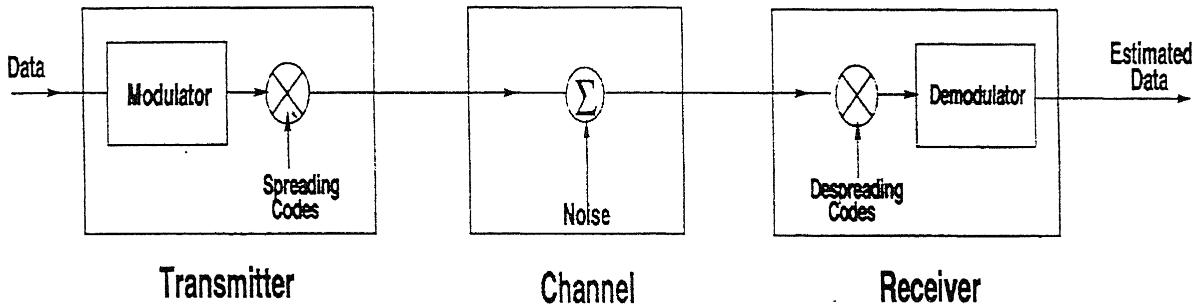


Figure 2.1: Baseband DS-CDMA system

DS-CDMA system. The modulated data is spread by the spreading code and passed through the channel. The received signal is multiplied by the despreading code which is a synchronous exact replica of the spreading code.

The amount of performance improvement that is achieved through the use of spread spectrum is defined as the Processing Gain (PG) of the spread-spectrum system. PG is defined as the ratio of the spreading code rate to the symbol rate i.e.

$$G = \frac{T_d}{T_c} \tag{2.1}$$

where T_d and T_c are symbol and chip durations respectively.

Consider a binary valued data signal *a(t)* being modulated by a wideband spreading signal *b(t)* by applying both the signals to the multiplier for a baseband system. The data signal is defined as

$$a(t) = \sum_{i=0}^{\infty} a_i u(t - iT_d) \tag{2.2}$$

where $\{a_i\}$ is the transmitted symbol sequence and $u(t)$ is the rectangular pulse of duration T_d and unit energy. The spreading signal $b(t)$ is defined as

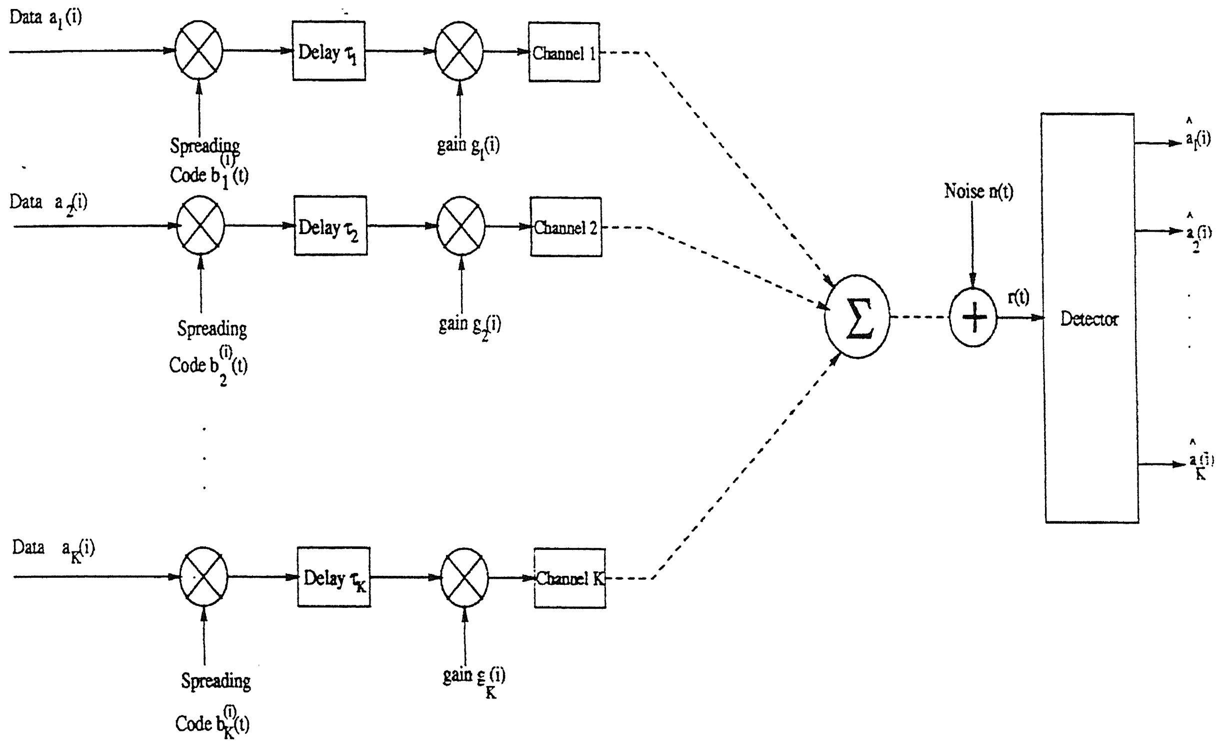


Figure 2.2: Transmit Model of an asynchronous DS-CDMA system

$$b(t) = \sum_{j=0}^{\infty} b_j \psi(t - jT_c) \tag{2.3}$$

where $\{b_j\}$ is the chip sequence and $\psi(t)$ is the chip pulse of unit energy.

Since the chip duration T_c is much smaller than the symbol duration T_d, multiplying the data sequence by the spreading code will result in each data symbol being divided into G chips where G is the processing gain. Thus the transmitted signal can be written as,

$$\begin{aligned} m(t) &= a(t)b(t) \\ &= \sum_{i=0}^{\infty} a_i \sum_{j=iG}^{(i+1)G-1} b_j \psi(t - jT_c) \\ &= \sum_{i=0}^{\infty} a_i \sum_{j=0}^{G-1} b_{j+iG} \psi(t - iT_d - jT_c) \end{aligned} \tag{2.4}$$

where a_i is the i^{th} transmitted bit.

Consider the asynchronous DS-CDMA system shown in Fig. 2.2 for K users. The binary valued data stream from the k^{th} user is denoted as $\{a_k^{(i)}\}$. This data stream after being spread by a unique signature sequence (also called the "code" in code division multiple access) is converted from discrete time to continuous-time via the pulse shaping operation. The channel introduces multipath effects, asynchronism and attenuation of the signal. The unstructured interference is usually modeled as an additive white Gaussian noise process denoted as $n(t)$ where $n(t)$ has zero mean and unit power spectral density. The continuous-time signal which is the sum of all the users's transmitted signals is observed at the input of the receiver and is denoted as $r(t)$.

In this thesis it is assumed that the users transmit *asynchronously*, since this can easily be modified for a synchronous system. In a DS-CDMA system employing long spreading codes different types of asynchronism can occur. In a symbol synchronous system the symbol boundaries of the different users are aligned thus the interference is from a single symbol interval for the user of interest. In chip synchronous and symbol asynchronous systems the chip boundaries are aligned thus interference for a particular user symbol may be from two symbols of other users. Third type is the chip asynchronous system where the chip boundaries of the users are also not aligned. In this thesis we have considered a symbol asynchronous but chip synchronous system. As the sequences should be ideally aperiodic, it is reasonable to model each element of them to be an independent random variable. Hence, we adopt the aperiodic random sequence model which provides a good approximation to the long signature sequences employed in practical systems. The received CDMA signal $r(t)$ is the convolution of the transmitted signal of all K users and the channel impulse response plus the additive channel noise.

Assume that the transmitted signal can be given as

$$m(t) = \mathrm{Re}\left[\sqrt{2P_k}b_k(t-T_k)exp(j\omega_c(t-T_k))\right] \tag{2.5}$$

where,

k is the user of interest,

P_k - power for the kth signal,

ω_c - carrier frequency,

T_k - delay that models the asynchronous system.

The sequence $\mathbf{b^{(k)}}$ is used to spectrally spread the data symbols to form the signal,

$$b_k(t) = \sum_{i=-\infty}^{\infty} a_{(k)}^{\lfloor i/N \rfloor} b_k^{(i)} \psi(t - iT_c) \tag{2.6}$$

where, the chip duration T_c is given by $T_c = T/N$

N - Number of chips per symbol interval

$\psi(t)$ - the common chip waveform for all signals.

The k^{th} user is provided with a randomly generated signature sequence
$\mathbf{b_k} = (\ldots, b_k^{(0)}, b_k^{(1)}, \ldots, b_k^{(N-1)}, \ldots)$
The elements $b_k^{(i)}$ are independent random variables such that $\mathrm{E}\left[b_k^{(i)}\right] = 0$ and
$\mathrm{E}\left[|b_k^{(i)}|^2\right] = 1$
a_k is the data sequence $= (\ldots, a_k^{(0)}, a_k^{(1)}, \ldots, a_k^{(N-1)}, \ldots)$
with a symbol duration of T seconds. Assume that the data symbols $a_k^{(j)}$ are random variables with $\mathrm{E}\left[|a_k^{(j)}|^2\right] = 1$.

Consider asynchronous reception of the K users uncoded signal through single path channels

$$r(t) = m(t) + n(t) \tag{2.7}$$

For a channel corrupted by AWGN with two sided PSD $N_0/2$, the received signal $r(t)$ for the desired user 1 can be written as,

$$\begin{aligned} r(t) &= \sqrt{2P_1}g_1 b_1(t - T_1 - \tau_1)exp(-j\omega_c(T_1 + \tau_1)) + \\ & \sum_{k=2}^{K} \sqrt{2P_k}g_k b_k(t - T_k - \tau_k)exp(-j\omega_c(T_k + \tau_k)) + n_\omega(t) \end{aligned} \tag{2.8}$$

τ_k and g_k represent the delay and the complex gain associated with the the signal from the kth transmitter.

The general problem of multiuser detection is to decide which data vector $\mathbf{a} = [\mathbf{a_1}, \mathbf{a_2}, \ldots, \mathbf{a_K}]$ from the set of message vectors was transmitted by all users given the received signal $\mathbf{r}$ and the spreading vector $\mathbf{B} = [\mathbf{b_1}, \mathbf{b_2}, \ldots, \mathbf{b_K}]$. Note that, due to asynchronism, boundaries of the observation interval will not, in general, coincide with symbol boundaries of all users. The signal received from any particular user will thus be determined by all the complete and partial symbols of that user in the observation interval.

The received vector $\mathbf{r}$ can also be described through matrix algebra as

$$\mathbf{r} = \mathrm{S}\mathbf{a} + \mathbf{n} \tag{2.9}$$

where $\mathbf{S} = [\mathbf{s_1}, \mathbf{s_2}, \ldots, \mathbf{s_K}]$ is a $\mathbf{N} \times \mathbf{K}$ matrix and $\mathbf{a} = [\mathbf{a_1}, \mathbf{a_2}, \ldots, \mathbf{a_K}]$ is the data vector. The matrix $\mathbf{S}$ contains all information about the multiple access channel and may be expressed as

$$\mathbf{S} = \mathbf{B}\mathbf{G} \tag{2.10}$$

where $\mathbf{B} = [\mathbf{b_1}, \mathbf{b_2}, \ldots, \mathbf{b_K}]$ is a $\mathbf{N} \times \mathbf{K}$ matrix formed by all user's spreading codes and $\mathbf{G} = [\mathbf{g_1}, \mathbf{g_2}, \ldots, \mathbf{g_K}]$ is a $\mathbf{K} \times \mathbf{K}$ diagonal matrix formed by the received signal amplitudes.

Cross-correlation of 2 user's spreading codes is usually defined as

$$\rho_{\mathrm{ij}} = \mathbf{b_i^H}\mathbf{b_j} = \sum_{n=1}^{N} b_i^*(n)b_j(n) \tag{2.11}$$

The *correlation matrix* is defined as

$$\mathbf{R} = \mathbf{S^H}\mathbf{S} = \mathbf{G}\mathbf{B^H}\mathbf{B}\mathbf{G} \tag{2.12}$$

which has the element in its i^{th} row and j^{th} column as r_{ij}. Normally in the literature $\mathbf{S^H S}$ is defined as the correlation matrix.

2.2 Conventional Detector

The conventional single-user detector simply performs despreading operation on the received signal vector after carrier demodulation. The match filter statistic for user k can be written as

$$\begin{aligned}
\mathbf{y_k} &= \mathbf{s_k^H r} \\
&= \mathbf{s_k^H S a} + \mathbf{s_k^H n} \\
&= g_k a_k + \mathrm{MAI_k} + z_k
\end{aligned} \tag{2.13}$$

where $\mathrm{MAI_k}$ is the multiple access interference seen by user k and z_k represents white Gaussian noise. The decision for user k is made according to the value of y_k as if the MAI were Gaussian distributed. Thus if the signature sequences were orthogonal the MAI vanishes and each user enjoys a single-user channel and the conventional detector is optimal. In a cellular environment however, this is not the case. Main reason is due to asynchronicity of the user's transmission coupled with different time delays for their transmission and mobility

makes it impossible to have orthogonal spreading codes. Thus due to non-orthogonality the MAI becomes excessive if proper power control is not maintained resulting in what is known as the near-far problem. However if there is no information about the spreading codes of other users, the conventional detector is the optimal detector since MAI can only be treated as a noise sequence which cannot be reduced.

2.3 Necessity for Multiuser Detection

The single-user detector that is the conventional detector has inherent shortcomings, which are difficult to overcome for achieving higher capacity for the DS-CDMA system. These shortcomings can be summarized as below.

1. This receiver ignores the rich structure of the MAI by treating it as a white Gaussian noise, which degrades the performance. Even if no noise is present this interference will be treated as noise and hence an interference floor exists, which hampers in getting low bit error rate (BER), which is the key requirement for high data rate transmission of data and video in the proposed third generation system.

2. The conventional detector is sensitive to near-far problem. If an interfering user is much stronger than the desired user, the matched filter output for the interfering user will be large enough to cause decision errors. In the existing IS-95 system strict power control has been utilised to overcome this problem. However, strict power control is difficult to achieve in a fading environment like the wireless communications scenario. Also the overhead associated with feedback-based power control may turn out to be excessive in the proposed packet based CDMA systems.

3. Even the use of orthogonal spreading sequences in the system will not be of much help in the correct detection as the orthogonality among the different asynchronous users will be lost in the fading and multipath channel prevailing in the mobile environment.

Thus in order to successfully decode the users in a DS-CDMA system the most important issue to be resolved apart from the multipath propagation problem, is the MAI. Multipath propagation can be somewhat alleviated by use of RAKE receiver [21] to our advantage, whereas for MAI either joint detection techniques or explicit elimination are possible options.

Multiuser detection can eliminate MAI caused by active users in a DS-CDMA system.

But due to practical limitations in the implementation of the highly complex optimal detector [4], suboptimal approaches have been explored. These suboptimal approaches utilize the cyclostationary nature of the MAI at the chip level to approximate either the channel amplitude, phase and time delay while being aware of the spreading sequence of the interfering and desired user. Blind approaches are also being explored in the case of the decentralized receiver where it is not feasible to have knowledge of the interfering users spreading sequence. Another interesting way of suppressing MAI is to explore the spatial relationship between a user and the interferers and to utilize the steering capability of an antenna array [12], etc.. At present the capacity of the DS-CDMA system ([1]) is limited by the uplink capacity and hence the maximum thrust of the research has been focussed on increasing the capacity in the uplink side. Focus of this thesis is on uplink i.e. mobile to base station transmission, hence knowledge of the spreading sequences of all the users except the interfering users from the adjacent base stations is available and also the requirement for detection of all the users either singly or jointly is there.

2.4 Optimal Detector

This receiver structure is derived based on minimizing the squared Euclidean distance between the received signal and the sum of the K asynchronous user signals, i.e. the total transmitted signal. Thus, the presence of all K users simultaneously sharing the channel is accounted for arriving at the Maximum Likelihood (ML) receiver. The primary difference between the structure that evolves from such an approach and the conventional structure is that *joint sequence* decisions are made on the set of K mathced filter outputs as opposed to individual bit-by-bit decisions on each matched filter output alone.

2.5 Multiuser Detection methods:

Under the common head of multiuser detection we find a wide range of receivers. These can be classified as either using short spreading sequence or a long spreading sequence with long spreading sequence schemes normally also applicable for short spreading sequence systems. These systems differ vastly in complexity and performance. The complexity being in the

number of computations per data bit detected, while performance can be characterized by bit error rate, capacity improvement, near-far resistance, etc.. We can also differentiate different multiuser detection strategies by separating them as uplink based, downlink based and those which can be utilized in both the systems. They can be further classified as follows. Fig. 2.3 shows the different types of multiuser detection techniques.

1. Centralized and Decentralized Multiuser Detectors: The centralized receivers make use of side information about all interfering users (except the interfering users from the adjacent base stations) like channel parameters, timing information, spreading sequences etc.. These receivers are best suited for base station processing (uplink) where all this side information is either available or can be estimated continuously. Examples of this type include [8].

   The decentralized receivers exploit knowledge of the propagation channel parameters, the timing information, spreading sequence etc., of the user of interest only, which remarkably is the same information being used in the conventional matched filter receivers where MAI is totally ignored. These receivers are best suited for mobile-station processing (downlink), where information related to the other users is either difficult to obtain or forbidden because of the privacy reasons. To send this information regularly to all the users will be a loss of the resources like bandwidth and capacity of the system. Also the information regarding the interfering users may not be useful in the mobile environment where fading and multipath propagation highly restricts the utility of such information. But the advantage, which is available in the case of the downlink receivers is either due to pilot signal or a coherent transmission. All the signals including the desired signal travel the same distance with same propagation condition and hence the time delay and channel parameters remain the same and the orthogonality property can be exploited for detection. Thus the complexity of the downlink receivers is likely to be less.

   However the uplink receivers can handle more complexity due to centralized detection and as such all the users are required to be detected. While centralized detection in the downlink is not likely to give that much improvement vis-a-vis the complexity involved. The example of these type of detectors are [13]. Methods employed in all the above

receivers whether in uplink/downlink or centralized/decentralized can be classified as linear or nonlinear detectors.

2. Linear and Non-linear Multiuser Detectors: In the linear MUD's a linear transformation is applied on the received signal $\mathbf{r}$ to get new transformed data for detection without having to compute the estimates of the users' signals, $\mathbf{r}_k$, k = 1,2,...,K, as an intermediate step. The non-linear multiuser detection techniques estimate the users' signal as an intermediate step before finally detecting the signal. The interference cancellation MUD's a type of non-linear multiuser detector can be further classified in the following subheads.

    - Successive Interference Cancellation (SIC)
    - Parallel Interference Cancellation (PIC) which can be further classified into these subheads or combination of these sub-heads.
        - Single-stage and Multistage PIC
        - Adaptive and Non-Adaptive PIC
        - Soft Decision and Hard Decision PIC : Soft decision just spreads each output signal as is from a correlator with each user's code. In the hard decision, because each interference signal is bit-decided from the output signal of a correlator, an estimation of channel parameter is required to recover the signal strength and phase rotation.

2.5.1 Linear Multiuser Receivers

Linear multiuser detectors apply a linear mapping to the soft output of the conventional detector to reduce the MAI seen by each user. There are two types of these receivers viz. decorrelating or zero-forcing detector and minimum mean squared error (MMSE) receiver.

2.5.1.1 Decorrelating Multiuser Receivers

In the decorrelating receiver a linear transformation on the received data set is performed to remove the crosscorrelation present between the different users. The orthogonality between different users spreading sequences even if existing will not be present at the receiver due to

asynchronous transmission apart from multipath and fading. Hence, the finite crosscorrelation present between different users spreading sequences is removed by applying the inverse of the correlation matrix in order to decouple the data [6, 7]. Thus

$$\mathbf{y} = \mathbf{R}^{-1}\mathbf{S}^{\mathbf{H}}\mathbf{r} = \mathbf{d} + \mathbf{z} \tag{2.14}$$

where $\mathbf{R}^{-1}$ is the inverse of correlation matrix and $\mathbf{z}$ is the enhanced Gaussian noise. The main advantage of this technique is that the explicit knowledge of the received signal energies is not required. Also it is optimum in the near-far resistant sense. The negative point of this detector is that it causes noise enhancement. It requires computational complexity of the order $O(K^3)$ where K represents the number of users present in the system. The main disadvantage in respect of long code spreading sequence case is that crosscorrelation matrix has to be recomputed at every bit interval since the spreading sequence is not the same for each bit interval. Hence this method is computationally intensive and almost infeasible for the long code case resulting in the usage of suboptimal methods for matrix inversion or approximations for the matrix inversion as in [8]. Adaptive methods have also been developed for the approximation of this receiver.

2.5.1.2 Minimum Mean Squared Error (MMSE) receivers

In a time-invariant channel, the received vector sequence is stationary when data sequence is stationary. The statistics of the received sequence can then be learnt to minimize the error between the transmitted sequence and received sequence plus MAI and AWGN.

The simplest receiver on the above premise is the linear MMSE Receiver [18],[22] where the correlator for the user of interest is chosen to minimize the mean squared error with respect to the data signal. The MMSE receiver implements a partial modification where the modification is directly related to the background noise and hence tries to balance the interference removal vis-a-vis enhancing the background noise. The MMSE detector generally performs better in terms of BER compared to the decorrelating detector since it takes into account the background noise and utilises knowledge of the received signal energies. The main disadvantage of this receiver is that its performance depends on the correct estimate of the received amplitudes and also on the power of the interfering users. Also the MMSE receiver needs to implement matrix inversion from which comes the complexity of the de-

tector. Thus most of the suboptimal techniques of the decorrelating detector and some of its own are applicable for the approximation of the MMSE detector. The MMSE receiver for the long-code case exhibits the same problems as in decorrelating detector because of the matrix inversion at each chip which requires high computational complexity. Hence, suboptimal approaches have been proposed for the long code case.

2.5.2 Interference Cancellation Multiuser detectors

The basic concept of the interference cancellation (IC) is cancelling the interference by other users in the received data signal with minimum complexity in the system. The idea is to update a subset of the data or the simultaneous update of all the data. This gives the classification as parallel interference cancellation (PIC) and serial or successive interference cancellation (SIC). It is, of course, possible to devise IC schemes that are neither parallel nor serial and to choose the update schedule based on the receiver statistics or side information regarding the signal vectors. There has been tremendous research in the PIC detectors and variants of it because of the potential gains in capacity and performance it offers at reduced complexity even in long code spreading sequence case. The main advantage of the subtractive interference cancellation scheme is they are much simpler than the linear multiuser detectors, but their performance is considerably inferior and research is more focussed on the ways to improve their performance. The disadvantage of the IC scheme is they need to estimate the amplitude and carrier phase of all active users.

2.5.2.1 Serial interference cancellation (SIC)

The SIC method of interference cancellation [23] is the simplest one. This method without explicitly estimating the users powers, tries to cancel the other users interference as per their signal strength. For this it uses the outputs of conventional correlation receiver to rank the users instead of separate channel estimates, thereby reducing the receiver complexity. Also chip sequences can be fed back successively for improving performance.

2.5.2.2 Parallel Interference Cancellation (PIC)

Parallel processing of multiuser interference, simultaneously removes from each user, the interference produced by the remaining users accessing the channel. In this way, each user in the system receives equal treatment insofar as the attempt is made to cancel the MAI. Since the IC is done in parallel the delay introduced by the receiver to cancel out the interference is miniscule compared to that introduced by the SIC method. The structure of the PIC is much simpler compared to the linear multiuser detectors. For improving the performance of the PIC detectors, multistage PIC detectors were introduced. In multistage PIC detectors the estimates of $(n-1)^{th}$ stage symbol decisions are used to regenerate the MAI to cancel out the interference at the n^{th} stage from the received signal. However this did not guarantee improved performance as these receivers try to cancel out the full interference introduced by all the interferers by using the estimates of the data symbols from the previous stage. This was many a times degrading the PIC performance due to the wrong estimate of the data symbol in the previous stage being used to cancel out the interference. This brute-force cancellation was resulting in double the interference from that particular user and increased errors. This multistage PIC was modified by Divsalar et. al., [24] by introducing a weighted cancellation in different stages.

The main advantage of the multistage parallel interference cancellation scheme is in the flexibility of selecting the number of stages as per the requirement of the BER. For example during voice transmission, the BER requirement is not that much stringent and hence the stages in use can be less, whereas for the data transmission BER requirement is high and hence more stages can be user. This flexibility in number of stages selection is offered by the PIC as in the starting stages the correctness of the data decision is not known and as the stages increase the BER will go on reducing. In the multistage PIC the selection of Hard Decision decoding versus the Soft Decision Decoding in conjunction with partial cancellation versus complete cancellation is a research topic in itself and detailed evaluations have to be carried out before deciding on a scheme for a particular scenario. Intuitively soft decision decoding is likely to provide better performance with partial cancellation though complexity is likely to increase.

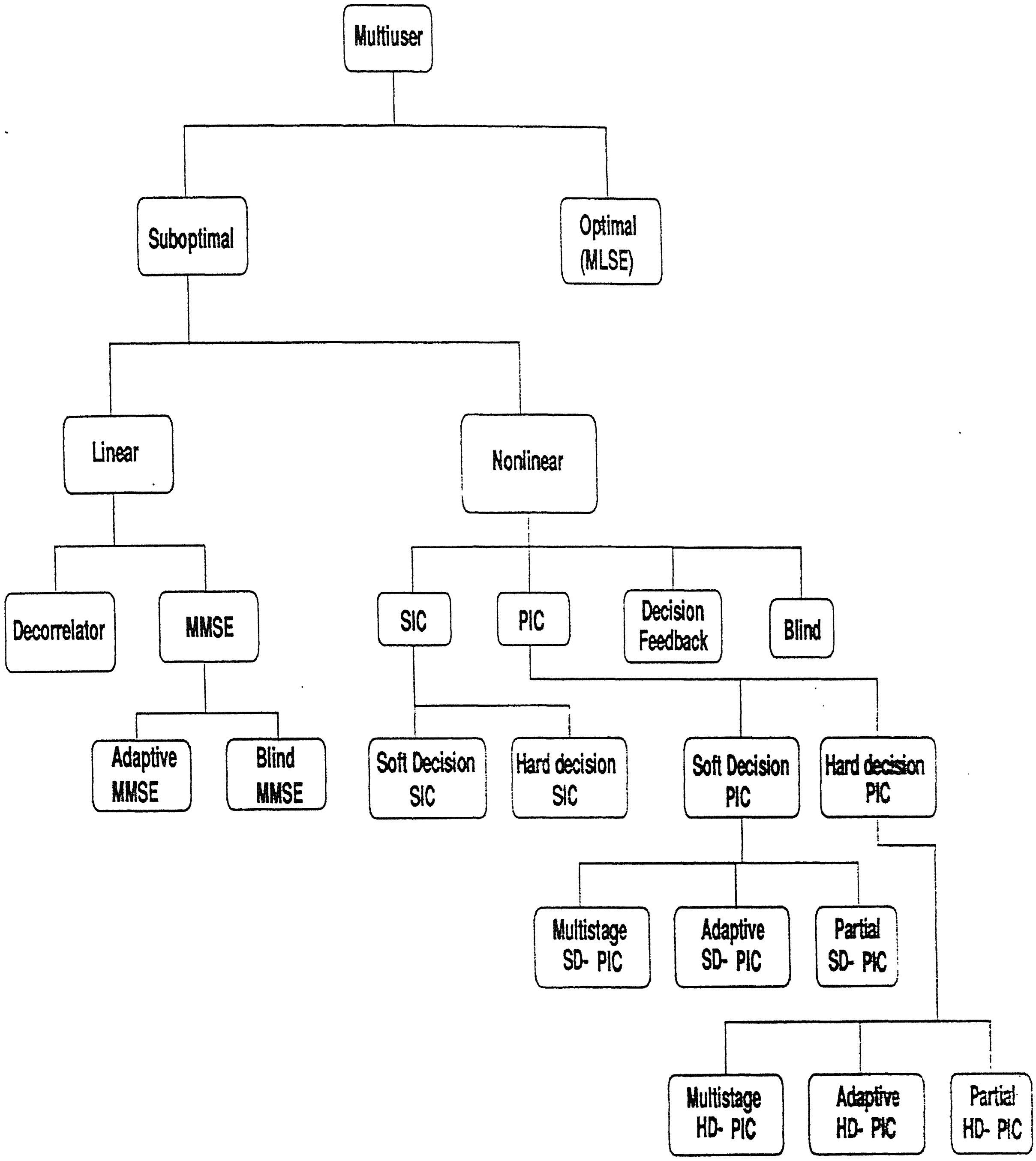


Figure 2.3: Multiuser Detection Techniques

Chapter 3

Interference Cancellation Techniques for Long Code Systems

The linear multiuser detectors capacity for canceling out the interference is limited due to dimensionality constraints i.e. when the signal space is larger than the length of the receiving filter there is no dimension left to null-out interference. Non-linear multiuser detectors like interference cancellation receivers are not limited by this problem. This chapter explains in detail the interference cancellation type of the multiuser detectors. This type of detection technique can be broadly divided into Serial Interference Cancellation, Parallel Interference Cancellation and their variants. Partial PIC detection techniques, the modified techniques of the conventional PIC techniques, which can be applied for a long-code DS-CDMA system have been considered in detail. In most of the existing literature, linear/non-linear MUD is considered in the context of a DS-CDMA system with BPSK modulation where MUD is decoupled from decoding of error control codes. Here an existing practical system model of mobile communication system viz. IS-95 mobile communication system's reverse link/uplink (mobile station to base station) has been used as a framework for the evaluation of the MUD techniques. The outline of this chapter is as follows.

Interference cancellation techniques have been explained in section 3.1 followed by section 3.2 where Serial Interference Cancellation technique has been explained. Conventional Parallel Interference Cancellation technique has been explained in section 3.3. Section 3.4 explains the Partial Multistage Parallel Interference Cancellation algorithm followed by the

two algorithms for long codes. This is followed by comparison of the long code MUD performance in section 3.6 Two modified algorithms for improving the performance of the multiuser detectors especially in the IS-95 environment have been presented in sections 3.7 and 3.8. Finally reverse link of the IS-95 system has been explained in Section 3.9, emphasizing the rationale for not employing the convolutional coding/interleaving.

3.1 Interference Cancellation Techniques

The decision driven/interference estimator based multiuser detectors are based on a heuristic concept which can be stated as follows. The received signal is composed of three parts, the desired signal, the aggregate structured multiuser interference, and the unstructured channel noise. The decision driven multiuser detector forms tentative decisions on the transmitted symbols and uses these decisions to generate an estimate of some or all of the aggregate structured multiuser interference. In each stage of a general multistage interference canceler, estimated interference for each user is subtracted from the received signal to obtain a signal with less interference. An estimate of interference for the k^{th} user is obtained by computing signal estimates for all users and adding up the signal estimates of all but the k^{th} user. This idea is quite intuitive in that, if we assume that the aggregate multiuser interference was estimated perfectly, the output of this operation is composed only of the desired signal and the additive, unstructured channel noise. This concept is the premise on which both Successive/Serial and Parallel Interference Cancellation techniques are based. In the case of SIC different users are detected serially as per their received signal energies. Thus first user is invariably detected by match filter detection where the decision statistic is subject of remaining users interference. This detection is then used to reduce the interference seen by the remaining users. Unlike SIC detection, PIC attempts to cancel all of the MAI for each user. Thus when the interference estimates are reliable, than better performance can be achieved by cancellation of all of the MAI in parallel rather than serially.

With regard to the form of the tentative decision device used at each iteration stage or for each user can take many forms i.e. hard decision, soft decision, etc.. Fig. 3.1 shows some of the tentative decision devices possible. The analysis of the non-linear decision device is very difficult.

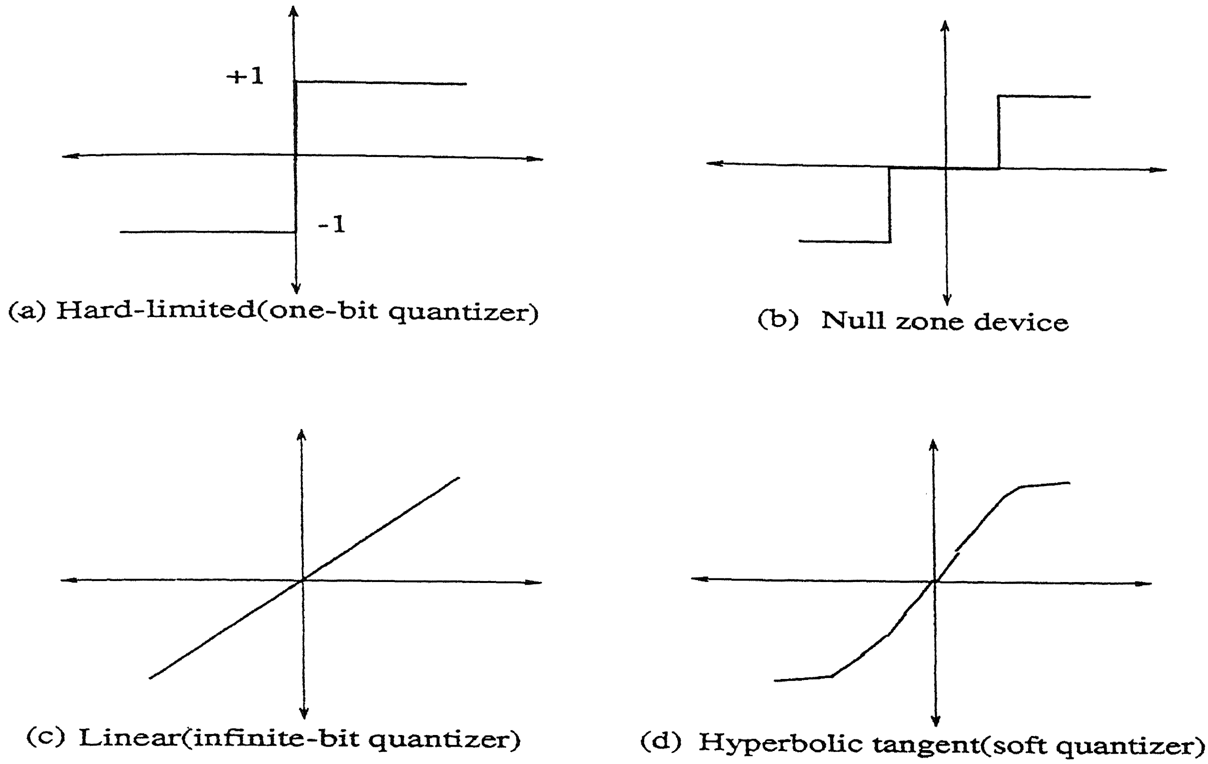


Figure 3.1: Tentative decision device functions

3.2 Serial Interference Cancellation

This type of multiuser detection technique has been explained in detail in [23]. There the users are detected as per the strength of their signal as obtained at the match filter output. In our simulation we have not done any ranking of the users, but assuming that the power control is perfect first users transmitted symbol in the current interval is detected first. Assuming the detected symbol being correct it is respread and subtracted from the received data to get a modified received data consisting of data of remaining users. In the same way remaining users transmitted symbols are detected. Thus as the number of users whose interference is subtracted increases the performance improvement obtained as shown by bit error rate reduction increases vis-a-vis the conventional matched filter detector. The main advantage of this type of detector is reduced complexity compared to the other techniques. The biggest disadvantage is the amount of delay involved for detection. Another disadvantage of this scheme is the fact that a specific geometric power distribution must be assigned to the users in order that each see the same signal power to background noise plus interference noise ratio. This comes about because of the fact that with successive cancellation the first

user to be processed sees all the interference from the remaining $(K-1)$ users, whereas each user downstream sees less and less interference as the cancellation progresses.

3.3 Parallel Interference Cancellation

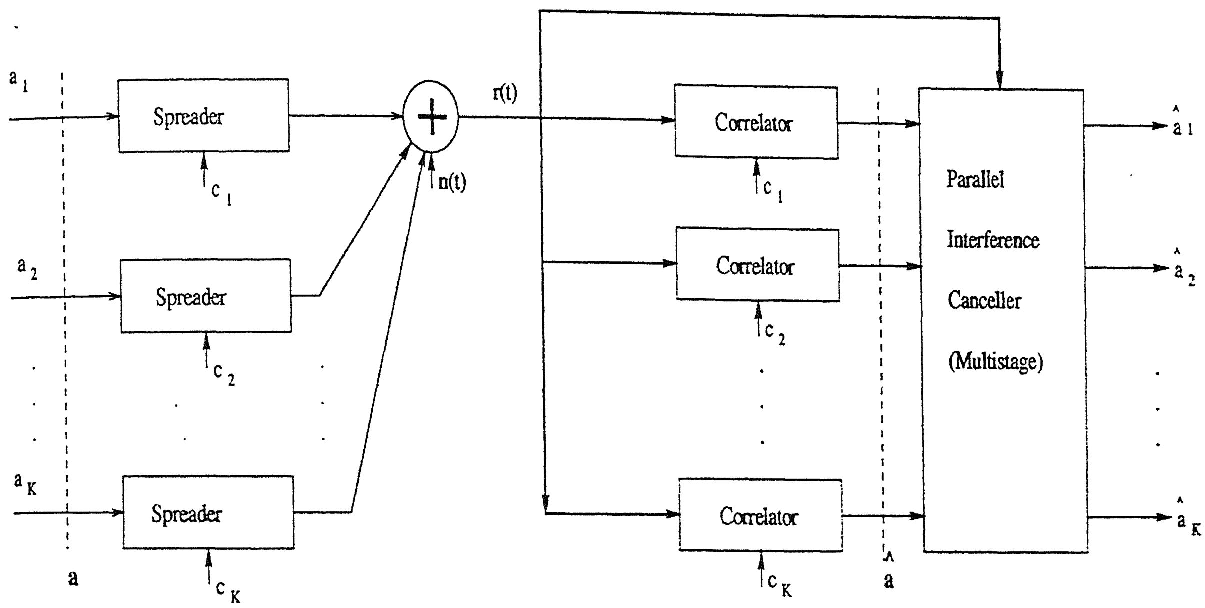


Figure 3.2: Receive structure of a typical PIC multiuser detector

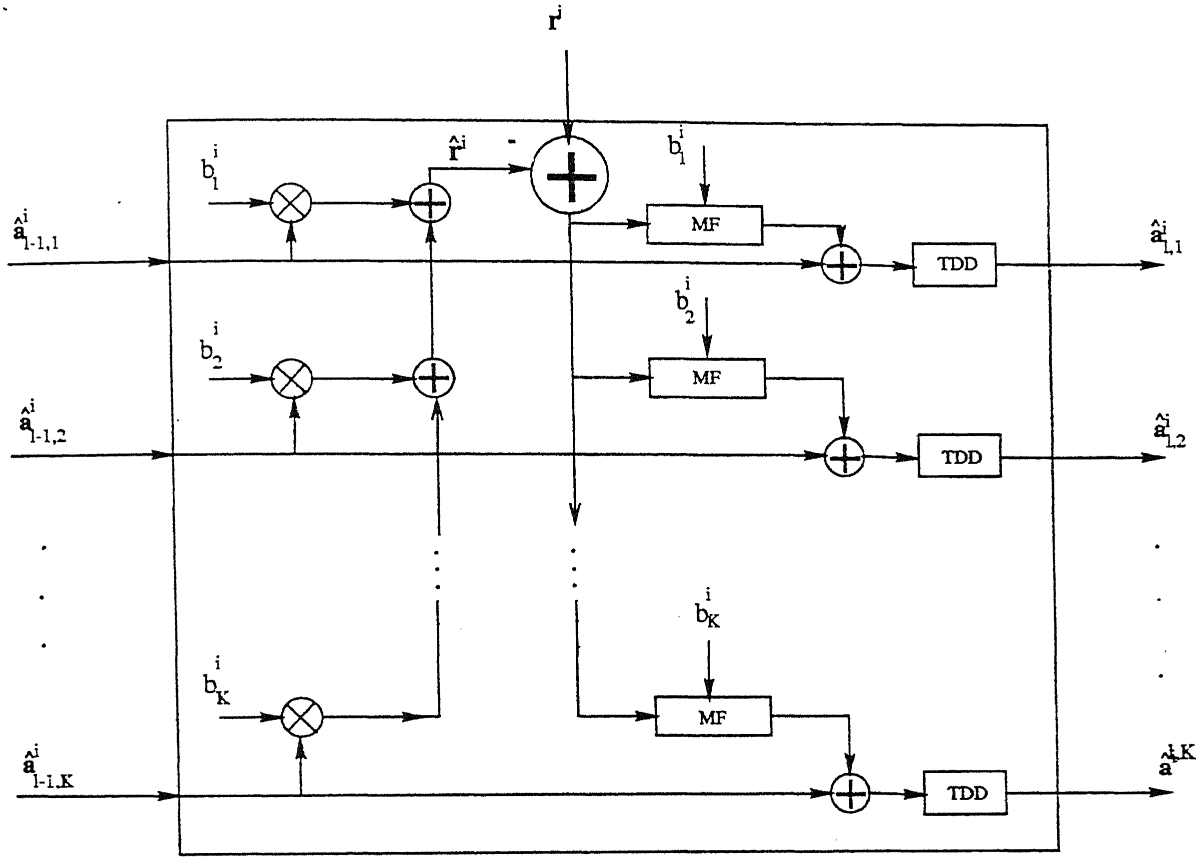
Figure 3.2 shows the general framework for the application of different PIC algorithms.. In different types of PIC techniques only the PIC block (may also be multi-stage) is modified for getting improved results. Henceforth only the PIC block will be described in detail.

3.3.1 Hard Parallel Interference Cancellation

Hard Parallel Interference Cancellation (HPIC), first called multistage detection and often just called Parallel Interference Cancellation (PIC), was first described for an asynchronous multiuser CDMA communication system by Varanasi and Aazhang in [11] where the multistage detector was derived from an analysis of the optimum, joint maximum likelihood detector. The same authors also presented the multistage detector for synchronous systems in [10] with a bit error rate analysis for the two-stage HPIC detector with a linear decorrelating detector front end. The main disadvantage of HPIC detector is the require-

ment of estimation of the received amplitudes of individual users for accurate estimation of interference for each user.

The detector selects in each stage the most likely transmitted symbol for each user in parallel assuming that the decisions made for all the other users in the previous stage are correct. The l^{th} stage of a multi-stage conventional PIC detector is shown in Figure 3.3. The



MF- Matched Filtering TDD- Tentative Decision Device

Figure 3.3: l^{th} stage of a conventional PIC detector

chip-matched filtered received signal vector $\mathbf{r}$ is fed into the detector, where

$$\mathbf{r} = \mathbf{BGa} + \mathbf{n} \tag{3.1}$$

At the first stage, previous tentative decisions are assumed to be 0. Assuming decisions for all users are correct for stage $(l-1)$, the detector first reconstructs the interference to user k from all the interfering user based on their decisions and then cancels it out from the received

signal. The residue signal for i^{th} symbol after $(l-1)$ stage for user k may be expressed as

$$\mathbf{r}_{l-1}^{i,k} = \mathbf{r}^i - \sum_{\substack{j=1 \\ j\neq k}}^{K} \mathbf{b}_j^i \hat{a}_{l-1,j}^i = \mathbf{r}^i - \sum_{j=1}^{K} \mathbf{b}_j^i \hat{a}_{l-1,j}^i + \mathbf{b}_k^i \hat{a}_{l-1,k}^i, \tag{3.2}$$

where $\hat{a}_{l-1,k}^i$ is the tentative decision made for user k at stage $(l-1)$ for the i^{th} symbol. This decision as explained earlier can be hard decision or a soft decision. This choice of the decision function influences the performance improvement remarkably. However the analysis of the soft decision function or non-linear functions is highly complex.

The residue signal is assumed to be interference free so that code-matched filtering can be performed to yield a current stage statistic for user k, which can be expressed as

$$\begin{aligned} y_{l,k}^i &= \mathbf{b}_k^{iH} \mathbf{r}_{l-1}^{i,k} \\ &= \mathbf{b}_k^{iH} (\mathbf{r}^i - \sum_{j=1}^{K} \mathbf{b}_j^i \hat{a}_{l-1,j}^i + \mathbf{b}_k \hat{a}_{l-1,k}^i) \\ &= \mathbf{b}_k^{iH} (\mathbf{r}^i - \sum_{j=1}^{K} \mathbf{b}_j^i \hat{a}_{l-1,j}^i) + \hat{a}_{l-1,k}^i \end{aligned} \tag{3.3}$$

Assuming that here linear decisions are made at the tentative decision device we have $\hat{a}_{l-1,k}^i = y_{l-1,k}^i$ and

$$y_{l,k}^i = \mathbf{b}_k^{iH} (\mathbf{r}^i - \sum_{j=1}^{K} \mathbf{b}_j^i \hat{a}_{l-1,j}^i) + y_{l-1,k}^i \tag{3.4}$$

Further analysis of linear interference canceler reveals that such detectors tend to converge to the decorrelating detectors provided the eigenvalues of the cross correlation matrix are less than 2 and sufficient number of stages are available. However the eigenvalue constraint is too strict to be satisfied in all but the simplest cases. This makes the conventional PIC unstable resulting in divergent operation, that is worse performance than the conventional match filter detector. It has been seen that the conventional PIC detector is useless for a system with the number of users comparable to the processing gain, since the chance of having an eigenvalue greater than 2 is so large that the detector suffers divergence for most of the codes. For the case of long spreading codes a portion of all code-sets has at least one eigenvalue of the code correlation matrix greater than 2 in a particular symbol interval resulting in the not so good performance (which is the average of good and bad performance of different users due to divergence in each interval due to a different user) and hence the

conventional PIC detector does not converge to the decorrelator even for very large number of stages.

A great deal of research on the topic of improving the performance of decision-directed multiuser detectors doesn't fall into the category of LPIC or HPIC detection and instead has centered around the mapping function from the soft decision statistics at the output of the first stage to the interference estimates used for cancellation. In the conventional HPIC detector with binary signaling used the sgn(.) operation. New research is focused on using multilevel quantizer, dead-zone nonlinearity and linear clipper interference estimation functions.

The conventional PIC detectors poor performance can be explained as follows over and above the analytical explanations presented in recent papers which gives the problem as due to eigenvalues of the cross correlation matrix greater than 2. Full cancellation may not be the best philosophy because when the estimates are unreliable, the full cancellation of the estimated symbols in the starting stages will increase the multiacess interference instead of reducing it and thereby degrading the performance. Thus in the starting stages where the decisions are not so sure it is better not to deduct any interference or deduct partially depending upon the reliability of the decision and as the decision improves the interference can be removed more in the later stages. Also if possible there can be negative cancellation to correct for an incorrect decision in earlier stages. This requires non-linear type of decision devices or some threshold type detection. Partial PIC technique is based on the above premise which is explained next.

3.4 Partial Parallel Interference Cancellation

A significant improvement to the PIC scheme was suggested by Divsalar and Simon in [24] where they proposed a weighted cancellation scheme. Here the current set of decision statistics is a weighted sum of the previous set of decision statistics and the statistics resulting from interference cancellation based on current tentative decisions. They considered both linear and non-linear decision functions based on joint Maximum Likelihood considerations. Each user's data bits were individually decided in a given interval to reduce the complexity of the system. Since, the exact knowledge of the user's data bits were not available they

used the estimates obtained in the previous stage to make a tentative decision in the present stage.

Thus, in general, the decision statistic for user k at stage l is a weighted sum of the statistics at stage $(l-1)$ and the statistic based on current cancellation, i.e.,

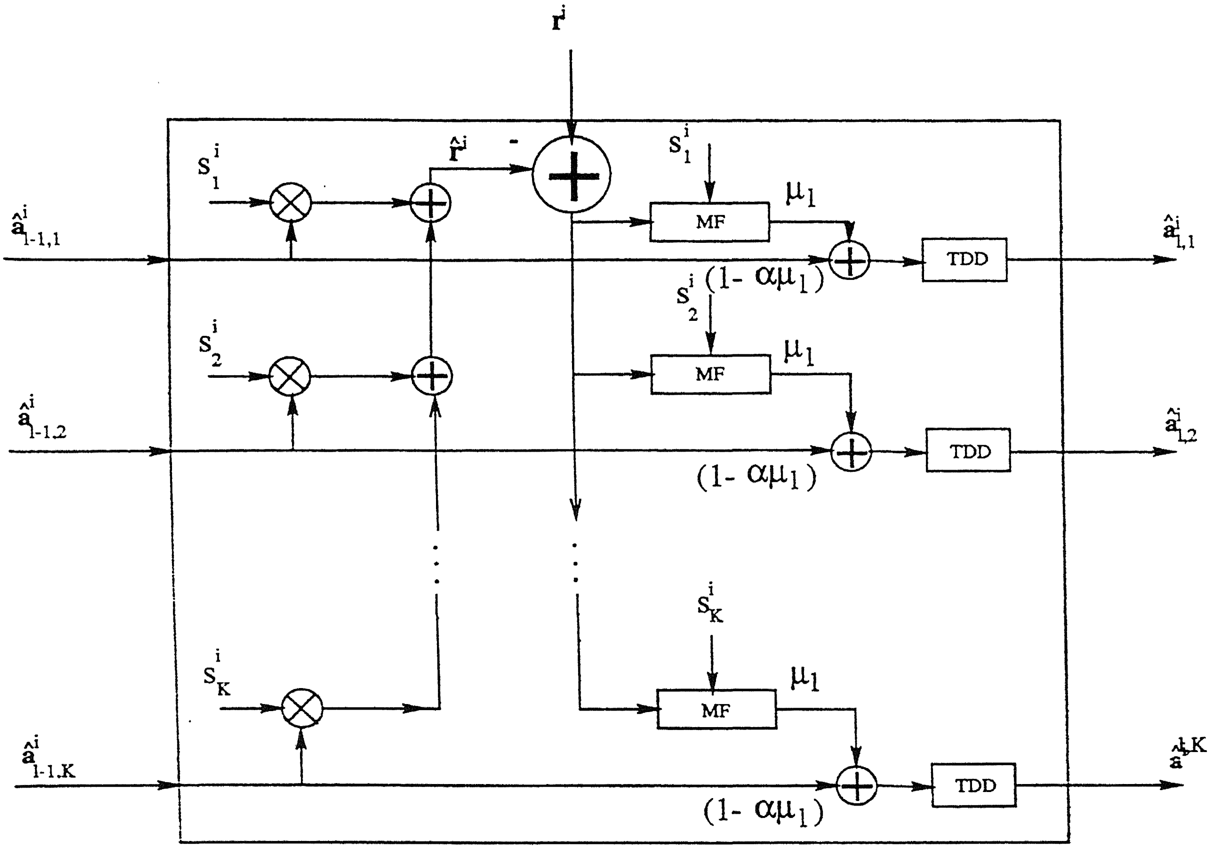
$$y_{l,k} = (1 - \alpha\mu_l)y_{l-1,k} + \mu_l \mathbf{s}_k^H(\mathbf{r} - \sum_{j=1}^{K} y_{l-1,j}\mathbf{s}_j) \tag{3.5}$$

here $\mathbf{s}_k$ represents the amplitude of the received signal for user k and μ_l represents the l^{th} stage weighting factor. This reduces to the conventional PIC scheme when $\mathbf{s}$ is replaced by $\mathbf{a}$ and $\mu_l = 1$ and $\alpha = 0$

Simulations have shown that a linear weighted PIC may outperform the decorrelating detector and even be comparable to the MMSE detector. When compared with the conventional detectors without interference cancellation the improvement obtained is dramatic at a complexity increase which is linearly proportional to the number of users. They considered a synchronous system of users which gives the worst case performance. However in the case of the asynchronous transmission more parameters are to be estimated namely the delays of the users etc. It was also concluded that using a hyperbolic tangent device for making the tentative decisions at the various stages of the cancellation process is superior to using either a hard limiter or linear device. The linear device, on the other hand has the advantage that the receiver implementation does not require knowledge of the user powers nor does it require carrier synchronization at the various stages.

It is still unclear in the literature why weighted cancellation dramatically improves performance. The weighting factors, are so far selected empirically and there is no known algorithm for finding suitable weighting factors efficiently. There is an attempt made to calculate the optimal weights of the stages in [17]. It was shown in [17] for a short spreading code system with a given number of cancellation stages, a unique choice of weights exists that leads to the minimum achievable Mean Square Error (MSE). Different optimality criteria can be adopted for calculating the weighting factors. Though bit error rate is the eventual criterion for a digital communication system, MSE as the criterion was considered as an indicator of the bit error rate performance, since it is a quadratic function of the filter weights which results in a unique minimum.

Fig. 3.4 shows the block diagram for the Partial PIC where weights for the l^{th} stage



MF- Matched Filtering TDD- Tentative Decision Device

Figure 3.4: l^{th} stage of Partial PIC detector [16]

have been shown. Here s represents the amplitude of the received signal for a particular user and μ_l represents the l^{th} stage weight.. It is shown that linear PIC needs exactly K stages to converge to the MMSE detector when $\alpha = \sigma^2$. Even when the given no. of stages are less, $l \leq K$ and any $\alpha \geq 0$, a unique optimal set of weighting factors exist that will lead to the minimum achievable MSE. However when $\alpha \neq \sigma^2$ the weighting factors are complex resulting in double the complexity in the system. This can be converted to real weighting factors resulting in suboptimal weights with reduced performance. Here the amplitude of the received signal is also used for calculating the weighting factors for each stage. Since σ^2, the noise level is not available at the receiver, hence an estimate is used. Thus these weighting factors are affected by mismatch in estimation of noise also. The ordering of the weights only affects the bit error rate achieved in the intermediate stages and has no effect on the final performance improvement achieved. These weighting parameters are dependent

on the eigenvalues of the channel correlation matrix. Effectively the weighting factors are dependent on the number of users, received signal level, noise level etc.

All the above papers considered only the short spreading codes for simulation and or analysis. Very few algorithms have been presented for long codes for multiuser detection using interference cancellation techniques.

3.5 Partial PIC Techniques for Long Codes

Two techniques for multiuser detection based on the partial PIC have been explained next.

3.5.1 Linear Parallel Interference Cancellation (LPIC) detector

Due to the use of long codes, the spreading codes as well as the corresponding channel correlation matrix changes every symbol interval. Hence the optimal set of weighting factors given for short spreading case will require to be computed and updated every symbol interval. As the solution to the optimal weighting factors involves eigenvalue decomposition, which has a cubic complexity in the number of users, such an approach is no better than implementing the MMSE detector directly. To overcome this updating of the weighting factors every symbol interval, averaging is done to get a fixed set of weighting factors. This is possible because the correlation matrix of a CDMA channel is highly structured and centered around the identity matrix and as a consequence its eigenvalues are densely distributed. Thus utilizing knowledge of the statistical properties of the channel correlation matrix fixed weights are obtained for some criterion. On this premise a detector has been proposed in [16]. Different criteria in making the compromise over all code-sets can be adopted here and may reach different solutions. As earlier in short codes the authors have chosen minimizing the ensemble average of the MSE over all possible channel matrices. It has been shown that for a m-stage PIC, the weights depend on the first $2m$ moments of the eigenvalues of the channel correlation matrix. It has also been shown that the moments are polynomials of the processing gain, the number of active users and the received signal energies. The computational complexity of on-line updating these parameters is proportional to the number of users but independent of processing gain. Fig. 3.4 is also applicable for this algorithm. The calculation of the weights as the number of stages increase becomes too complex.

3.5.2 Near Decorrelating Multistage Detector (NDMD)

In another technique [15], variant of the Partial PIC algorithm has been presented. The block diagram of this technique is shown in Fig. 3.5. Here D denotes delay of the input signal by one symbol duration. This proposed technique requires only one subtractor for each canceling stage. μ_l signifies the weighting factor for the stage l. The conventional detectors when reducing the interference remove the total first order interference moment while injecting the second order moment. Thus they convert the lower order of interference into higher order one. This detector retains first order interference moment partially while reducing the second order interference moment. This method is claimed to be independent of the received signal strength of the users while enhancing the background noise. However no method has been proposed for calculating the weights for each stage but numerical methods have been used to get the weighting factors for different number of users in different channel conditions for a DS-CDMA system.

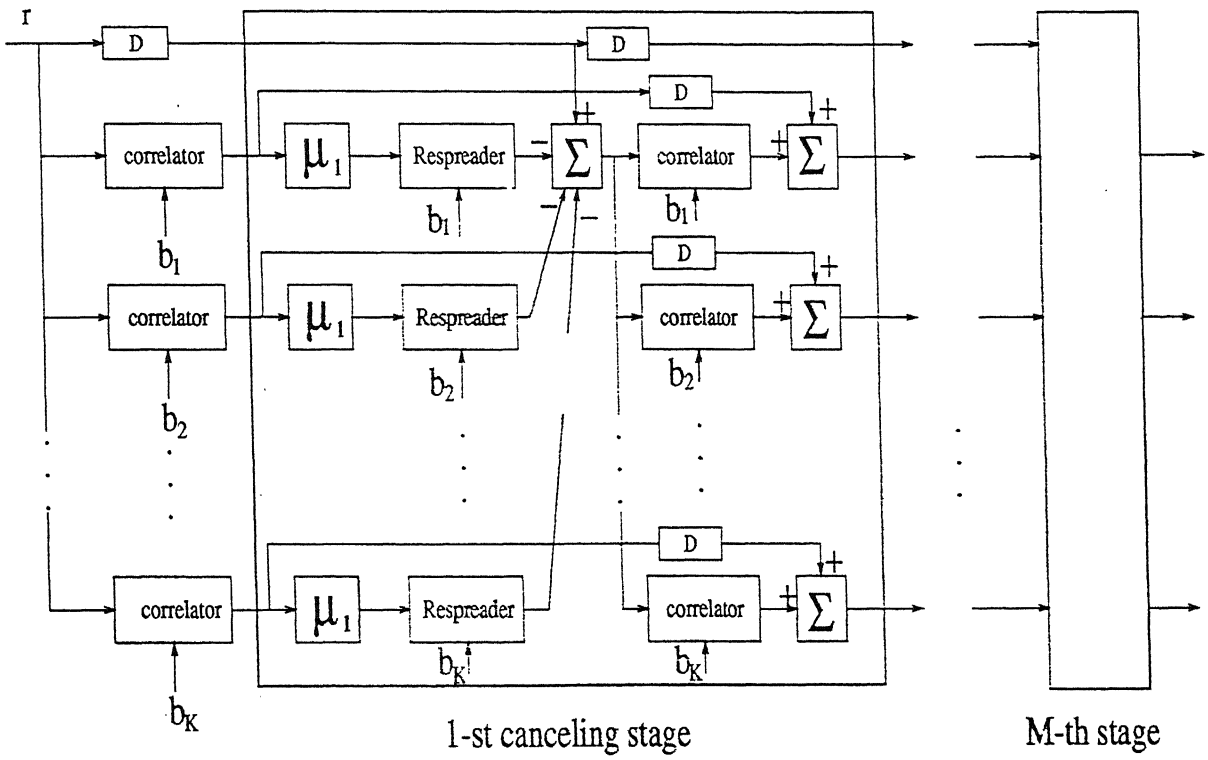


Figure 3.5: NDMD detector for long codes [15]

3.6 Comparison of Long Code MUD performance

In this thesis SIC and Partial PIC techniques as described above have been used for comparing the performance in IS-95 reverse link. The IS-95 reverse link is characterized more by interference reduction techniques and for this it uses convolutional codes, interleaving and Walsh modulation before OQPSK spreading so as to detect the signal at the base station by a conventional detector while using RAKE receiver for exploiting multipath effects. Thus to estimate a single symbol for interference cancellation techniques in a stage the delay required may be quite large which will be still larger for an asynchronous system with multipath effects. If large observation intervals cannot be tolerated (due to delay, complexity or adaptivity considerations), then due to asynchronism and/or multipath propagation effectively decrease the maximum allowable users and hence the BER available.

In this thesis received signal energies are not known or estimated. Also the optimum weighting factors were not available and were found by simulation and these factors were used for performance evaluation. In addition the delay experienced for the IS-95 system was too much. Depending upon the number of stages and using parallel operations the increase in delay was more than double the normal time for a conventional receiver for a single stage. The delay increasing linearly with the number of stages. For improving the performance of above multiuser detectors and for reducing the delay of the system following two algorithms have been proposed and applied to the LPIC and NDMD detector.

3.7 Walsh Chip based Interference estimator (WCIE) Detector

In the IS-95 reverse link data is first modulated by 64-ary Orthogonal Walsh modulation which is followed by Offset QPSK (OQPSK) spreading. Thus this feature can be utilized as a sort of Walsh Chip based Interference Estimation detection. That is instead of fully estimating the transmitted symbol for a particular user up to the tranmitted data, only despreading unto the Walsh chip can be done and this chip can be estimated and this estimation utilized for removing the interference stage by stage instead of full symbol estimation. This approach can reduce the delay substantially for IS-95 system since here the spreading factor is only

4. Also the complexity of the system will be reduced as the full spreading of the detected symbol will not be required. This modification has been applied for both the partial PIC algorithms viz. LPIC and NDMD detector and results show improved performance. However it is to be noted that this operation renders this system as a type of OQPSK system with very little processing gain but with orthogonal modulation before spreading whereas in the literature BPSK/QPSK spread data streams are considered with high processing gain but without the orthogonal modulation.

3.8 Threshold detector

It was also noticed from observations that if some threshold type decision arrangement was made for estimation of the Walsh chips in the intermediate stages after some stages in WCIE detector further improvement in performance can be obtained. In this modification the first two stage were kept same as the WCIE detector stage but next stages were used as the threshold stages i.e. the chip was decided only when the energy of the chip exceeded some threshold and then only this chip was respread to deduct the interference from the received data siganl. As expected there was improvement in the BER but this was limited, as stated earlier, due to the low spreading gain and dimensionality of the system. This modified detector is termed as threshold detector in this thesis and it has been applied for LPIC and NDMD techniques studied here.

3.9 IS-95 Reverse Link Model

IS-95 [3] is a Second Generation mobile communication standard based on DS-CDMA. Fig. 3.6 shows the actual reverse link block diagram in IS-95 system. Variable data rate signal either voice or data with rates 9.6, 4.8, 2.4 or 1.2 kbps are divided into frames with frame size 192, 96, 48 or 24 bits per frame. The frame is then convolutionally encoded at a 1/3 rate, resulting in 3 X 192 = 576 code symbols at full rate, or 28.8 ksps. For other data rates, the code symbols are repeated as necessary to cause each rate to input the same number of code symbols to the interleaver in a frame. The interleaver reads the data consecutively by column into an array of 32 rows and 18 columns; this procedure causes symbol repetitions

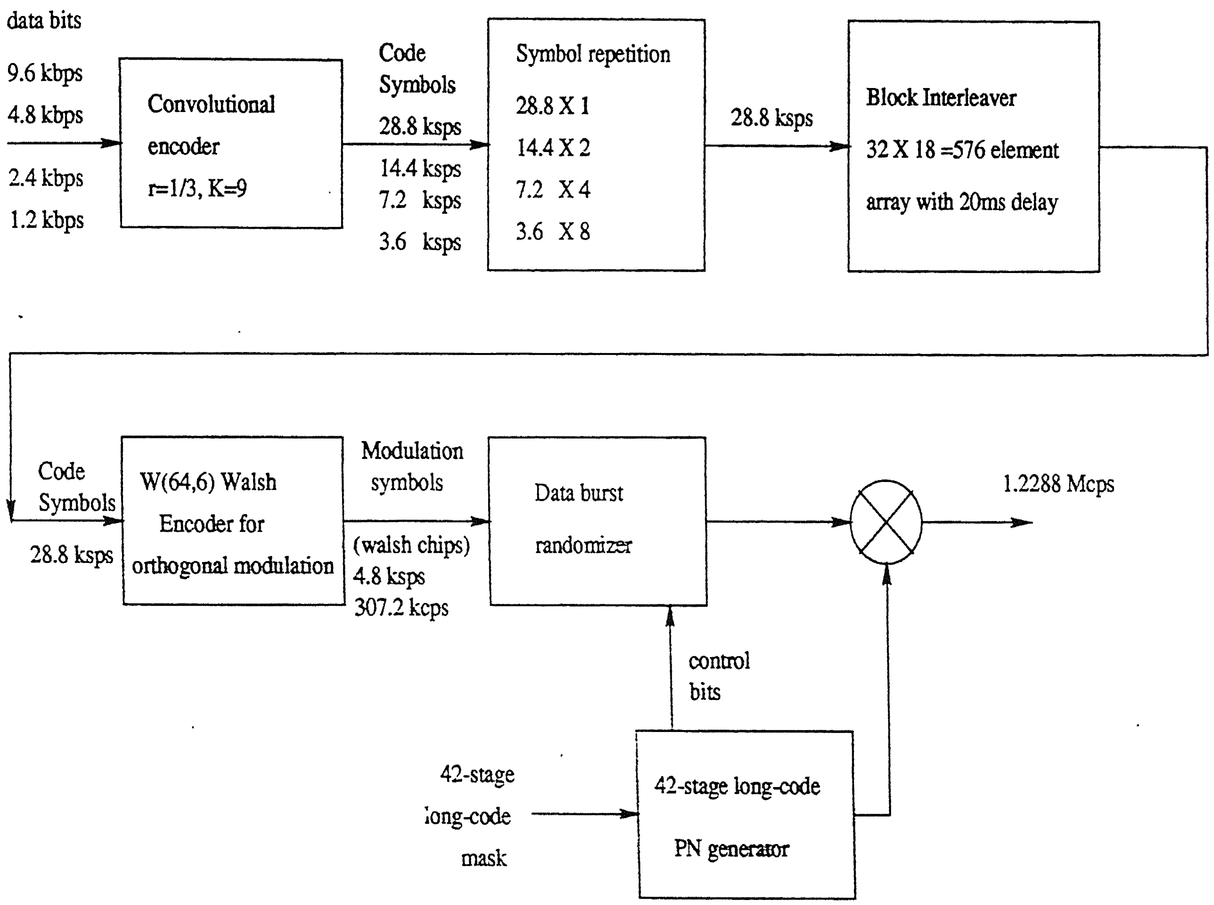


Figure 3.6: Reverse Traffic channel for IS-95 DS-CDMA system [25]

to be located in different rows. Interleaver has been used to reduce the burst errors in the received data. This interleaver operation introduces a delay of 1 frame (20 ms). This block is followed by the Walsh orthogonal modulation block where 6 symbols are converted to 64 Walsh chips. For signals less than full data rate, data randomizer block selects randomly the block to be transmitted out of the repeated blocks and the remaining blocks are gated off. These Walsh chips are then spread by the long spreading sequence generated by spreading sequence 42 stage long-code PN generator. These spread chips are then modulated by the zero offset short PN sequences.

In our implementation the simulation is done from the Walsh modulation block onwards, i.e. convolutional coding and interleaving operations have been omitted. This is done to get the improvement without the coding gain which is the normal practice in the literature. By selecting random bits as input to the Walsh modulation block there is no loss in randomness

of bits by not using the interleaver block. For generating different data rate transmission for different users uniformly distributed random numbers are used which signify the data rate of the user in a particular frame. Finally the sequence is not multiplied with the zero offset short-code sequences since here single cell operation is done and perfect synchronization is assumed though this may result in loss of some randomness of the transmitted data.

Chapter 4

Simulation Results

In this chapter SIC, LPIC, NDMD, WCIE and Threshold detector MUD techniques have been simulated under different channel conditions. The outline of this chapter is as follows.

Simulation environment has been fully explained in Section 4.1 with the differences in the reference papers vis-a-vis our simulation parameters clearly brought out and the rationale for selecting the particular parameters has also been given. Section 4.2 gives results under three different channel conditions for SIC and two Partial PIC algorithms i.e. LPIC detector and NDMD detector. Starting with simple multiaccess channel condition, followed by Gaussian channel results and finally the Rayleigh channel curves are plotted and their results discussed. This is followed by Section 4.3 where the results obtained by WCIE detector and Threshold detector in both the partial PIC algorithms are plotted for different number of users and different channel conditions as given above. Section 4.4 gives the results obtained for all the algorithms run under the same environment to depict relative performance. Finally in Section 4.5 near-far environment curves are plotted for the all the algorithms.

4.1 Simulation Parameters

Uniformly distributed six data bits are generated for feeding to the block of Walsh modulation. This Walsh block gives an output of 64 Walsh chips. These in turn are spread by 4 PN sequence chips for each Walsh chip. The long-code PN sequence is obtained from the 42-stage long PN sequence generator as given for IS-95 system [3]. Different users are given different offsets of the long code PN sequence for getting low cross correlation. They are

generated using different masks for each user. The transmission data rate of a particular user during each frame is randomly decided, i.e. at which of the four possible rates of 9.6, 4.8, 2.4 and 1.2 kbps, the transmission will be done. If the data rate is not full rate (9.6 kbps) which symbol out of the repeated ones will be actually transmitted is also decided randomly. If for example the data rate for a particular frame is 2.4 kbps there will be 8 repetitions of 3 six bit symbol sequences during a sub-frame interval (There are 4 such sub-frame intervals in a frame for 2.4 kbps data rate). Out of this 8 repetitions which one will be actually transmitted is decided randomly while the remaining 7 repetitions are gated off (i.e. not transmitted to reduce interference as has been done in IS-95 reverse link). Same way the symbols to be transmitted are decided for other data rates also. Baseband transmission has been utilized. Synchronization is assumed at the receiver end and power control is assumed perfect unless mentioned otherwise. Thus all the users signals are received at equal power at the base station. Symbol asynchronism is assumed but chip boundaries are assumed to be coinciding. The maximum delay between the users transmission for a particular symbol interval (which includes the propagation delay) is taken to be 64 Walsh chips. This delay is also generated randomly for each user which changes every frame interval. The weighting factors were obtained by numerical evaluation at each stage for large number of values of the weighting factors under identical conditions and selecting the value which gave the minimum BER and using these values, weighting factor for the next stage were obtained.

The main difference between the simulation conditions for the LPIC algorithm as used in [16] and here is the estimation of signal strength of the user signals at the receiver end. There signal strength of the users is estimated and is used for the calculation of the weighting factors while here this is not done to reduce the complexity of the system. Other reason for not estimating the signal strength is to reduce the errors which might have occured due to the incorrect estimates. Thus the results obtained here provide the minimum amount of performance gain which can be obtained by multiuser detection. The second important difference being the use of BPSK system with processing gain of 32 and symbol synchronous transmission. Here symbol asynchronous system has been used to depict the correct scenario on the reverse link in a mobile communication system. The third important difference is the use of minmisation of MSE as the optimality criteria for selection of weights which is different from the minimisation of the BER as the criteria for selecting optimal weight factors

here. Minimisation of the BER is the requirement of a system and that reflects the correct performance gain compared to the minimisation of MSE.

There is not much difference between the NDMD algorithm as implemented in [15] and as implemented here with the main difference being the use of differential BPSK for spreading and transmission and processing gain of 32. For SIC simulation also, signal energies are not estimated and arbitrarily first user is detected first. Results are presented next starting with the SIC method. In all the results where the results are plotted for number of stages the X=0 point on the Y-axis gives the conventional matched filter detection BER.

4.2 Results

4.2.1 Serial Interference Cancellation results

The curves for different number of users in MAI environment are shown in Fig. 4.1. The curves show the BER obtained when the detected users interference is subtracted to get less interference. From the curves it can be seen that as expected as the number of users detected increases, the BER for the users to be detected decreases. Fig. 4.2 shows the curves

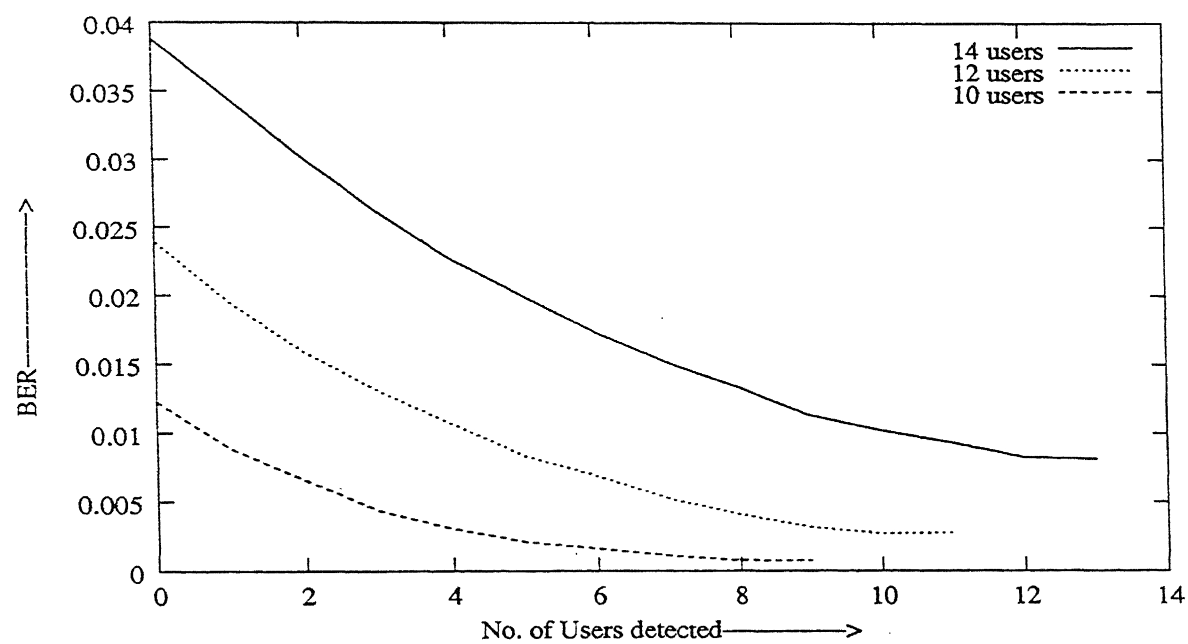


Figure 4.1: Curves for different number of users in MAI environment using SIC detection

for Gaussian channel condition for 10 users with varying SNR. These curves follow the same pattern as was available in the MAI environment. The oscillations in the curve is due to less number of iterations used in the simulations and would smooth out if more iterations are employed.

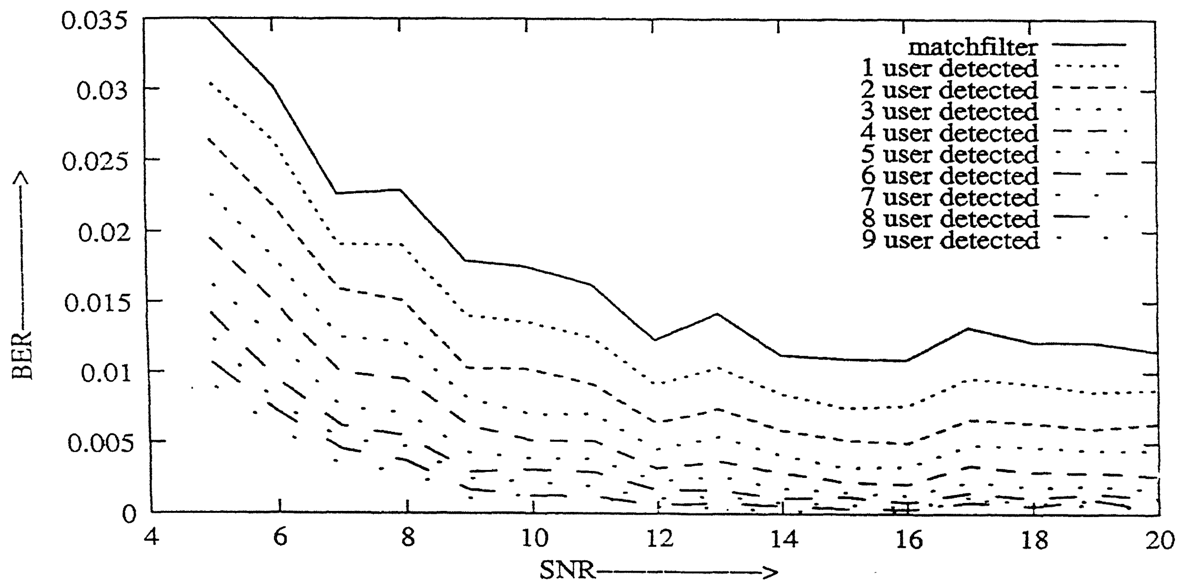


Figure 4.2: Curves for 10 users in Gaussian channel environment using SIC detection

Fig. 4.3 shows the curves for 14 users in a Rayleigh channel with varying transmitted power. Here the curves are drawn for number of users detected versus the BER.

4.2.2 LPIC detector results

The performance curves for varying number of users in MAI channel have been shown in Fig. 4.4. The curves are shown only for the best value of weighting factor for different number of users. It can be seen that when MAI is more the improvement obtained saturates after certain number of stages. After this the improvement is marginal. Fig. 4.5 shows the curves for a Gaussian channel for different SNRs for 10 users for optimum weighting factors. Compared to the MAI case, the improvement is reduced but as the SNR increases the channel will be approximately MAI one and hence the improvement increases. The optimum values of the weighting factors were obtained first by simulation and these weighting factors are different

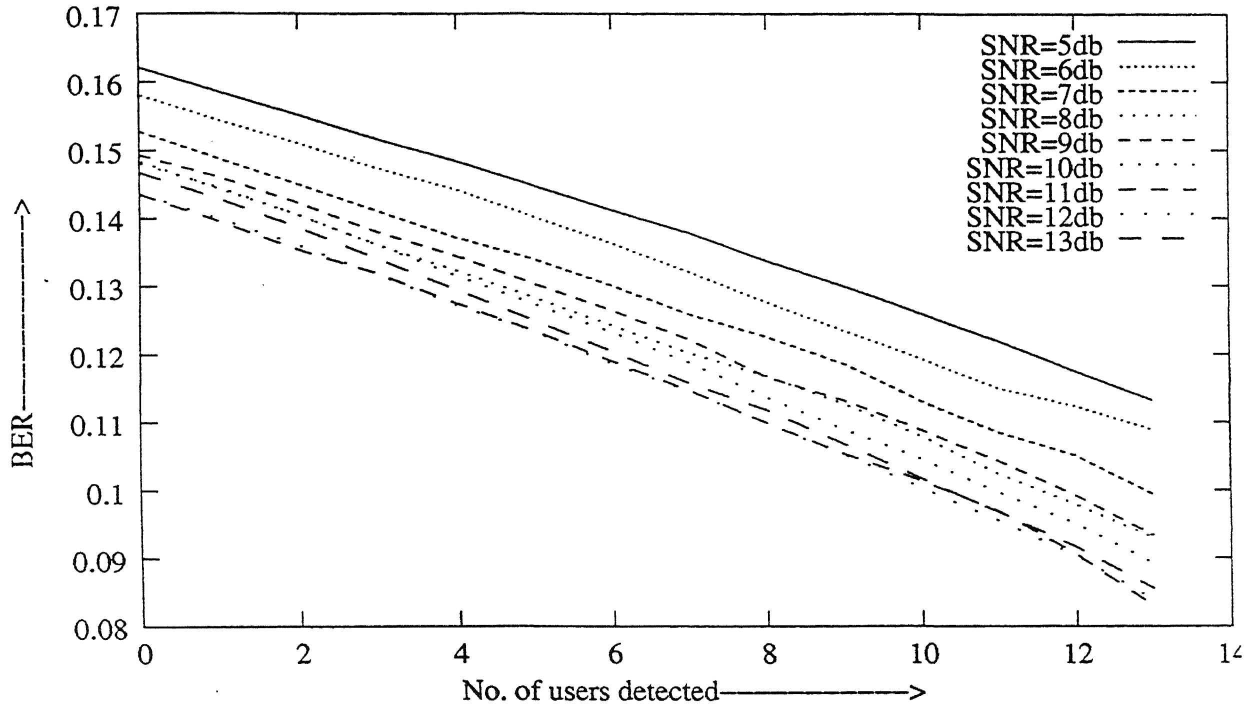


Figure 4.3: Curves for 14 users in Rayleigh noise channel condition using SIC detection

from those obtained for the case of MAI channel. Also there is variation in the weighting factor values for different values of SNR. Simulation were done for different number of users and only some curves for the 10 users have been shown. Also the weighting factors vary with the number of users.

4.2.3 NDMD detector results

Fig. 4.6 shows the BER plots for different number of users in MAI. The performance improvemement obtained by partial PIC detection is good. Fig. 4.7 shows the BER curves for 10 users with different SNR. For other number of users also the shape of the curves remains the same. The performance of the LPIC and NDMD detector is almost same. However one important point here is the weighting factor for both the algorithms are quite different. Weighting factors in the case of LPIC detector are different for different stages while in NDMD detector they are equal for all the stages and vary very little with the varying number of users. Also as was happening in the case of LPIC the improvement is negligible after 4 stages in the Gaussian channel case.

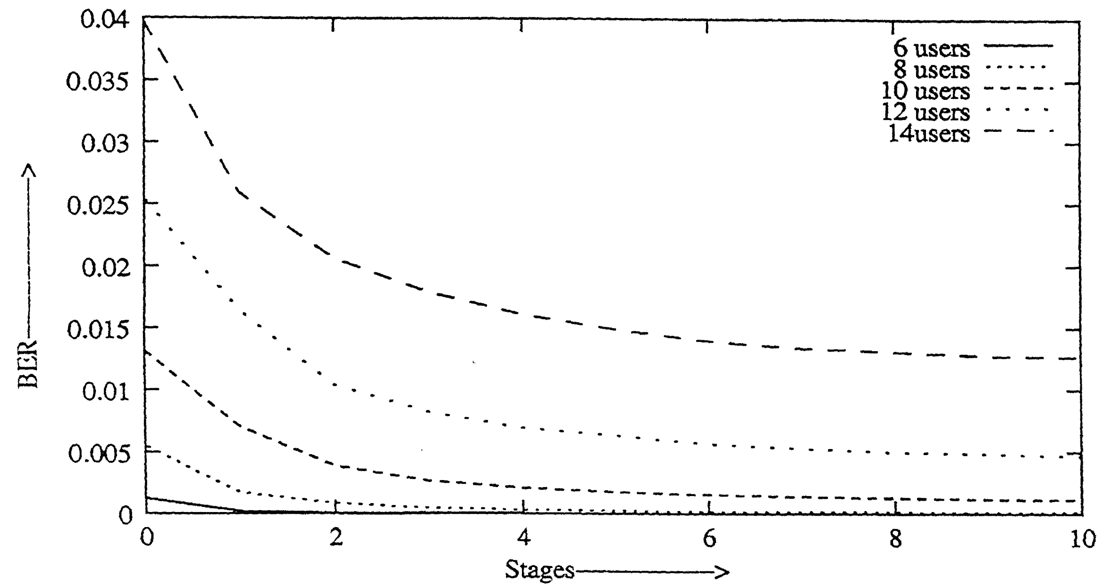


Figure 4.4: Curves for different no. of users in MAI channel condition using LPIC detection

Thus from the above curves it can be seen that in the Gaussian channel case the improvement is very less compared to the only MAI case. For the Rayleigh case and near-far environment case is still bad and hence those curves are not shown here. For improving the performance of the multiuser detectors, modifications as explained earlier were incorporated and simulations done for the optimum weighting factors. It is to be noted that the weighting factors were different than those obtained for the simple LPIC and NDMD algorithms.

4.3 WCIE and Threshold detector results

Two set of curves are plotted for WCIE-detection and threshold detection for both the detectors in Gaussian and Rayleigh channel condition. Figures 4.8, 4.9 gives curves for the Gaussian channel for WCIE-detection of the LPIC and NDMD technique respectively. The BER has improved compared to the earlier results and another advantage is the reduction in delay for detection of each symbol interval which specifically for IS-95 case was too high in the original LPIC and NDMD techniques. Similarly for Rayleigh channel curves are plotted for LPIC and NDMD-WCIE detectors in Figures 4.12 and 4.13. Similarly for threshold detection, curves are plotted in Figures 4.10 and 4.11 for Gaussian channel and Figures 4.14 and 4.15 for Rayleigh channel for LPIC and NDMD algorithms respectively. The thresh-

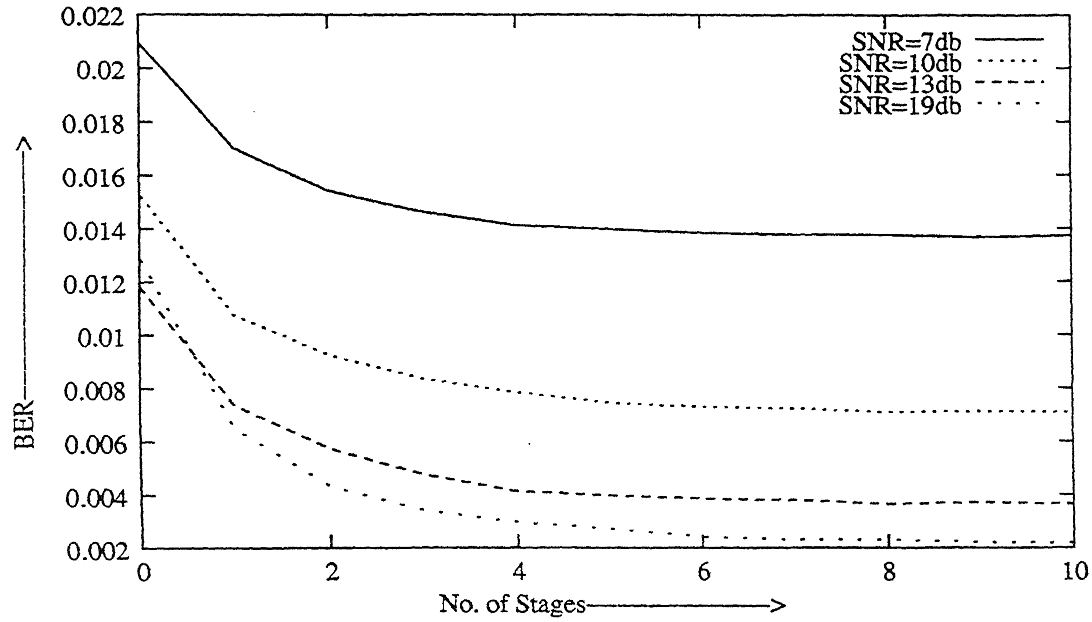


Figure 4.5: Curves for different SNR's in Gaussian channel using LPIC detection

olds for both the detectors were varied to get the maximum improvement and curves for maximum gains are plotted for different number of stages. However the threshold has been kept constant for all the stages. It was observed for LPIC threshold detection that the first threshold stage detection was giving higher BER than the previous stage which was available for different user case and also different threshold condition. Finally the delay of the Threshold detector is likely to be less as all the chips will not be required to spread and only the detected chips will be respread and hence additions and multiplications required will be less compared to both above type of detectors.

4.4 Comparison of the results of different detectors

In this section all the detectors were run concurrently to get the relative performance in the same channel and interference conditions. Results are plotted for all the three channel conditions viz. MAI, Gaussian and Rayleigh. Simulations were done for different number of users and curves are plotted for 14 and 10 user case for MAI channel in Figures 4.16 and 4.17 respectively. In the case of 14 users the variation in bit error rate is very clear for the WCIE detectors where BER increases and decreases from stage to stage which can be attributed to

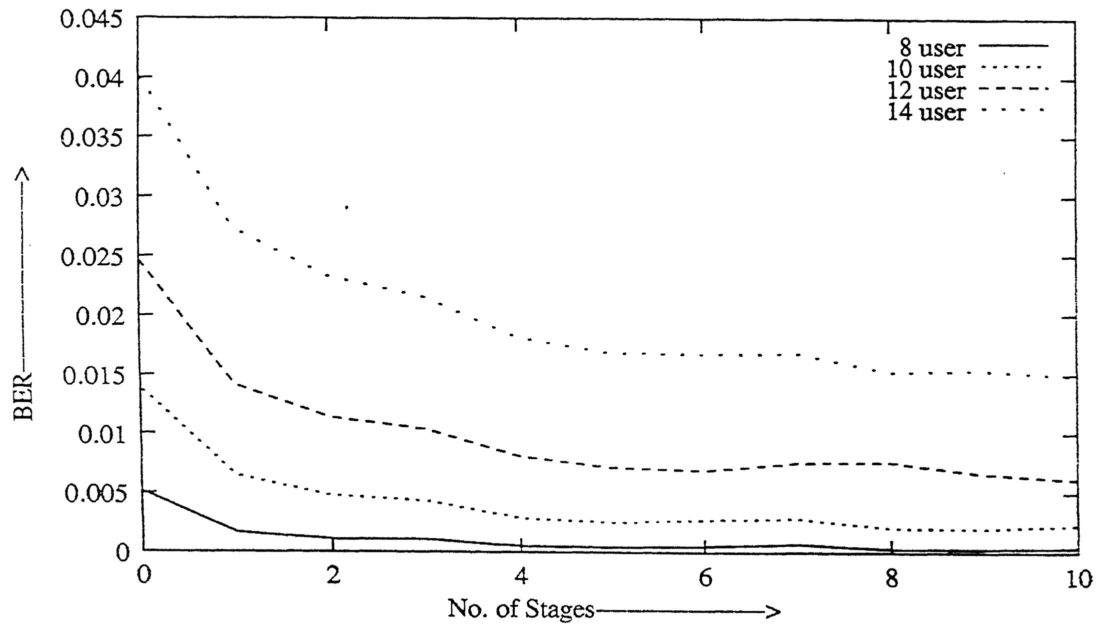


Figure 4.6: Curves for different no. of users for MAI channel using NDMD detection

more and less interference respectively. It is also seen that there is performance improvement in the results obtained by these modified techniques. Another interesting result was WCIE detection in LPIC was performing worse than the conventional LPIC for small number of users while there was no such problem with NDMD detection for MAI channel. Similarly combined results are plotted for 10 users case for Gaussian channel and Rayleigh channel in Figures 4.18 and 4.19 respectively. It was observed that the conventional LPIC detection was diverging for very low value of SNR as shown in the figure where it is taken to be 5db. When SNR was high improvement was obtained even in the case of LPIC detection as was seen in the earlier Gaussian channel results for the LPIC detection. It was also observed that the LPIC threshold detection performed better than the NDMD threshold detection.

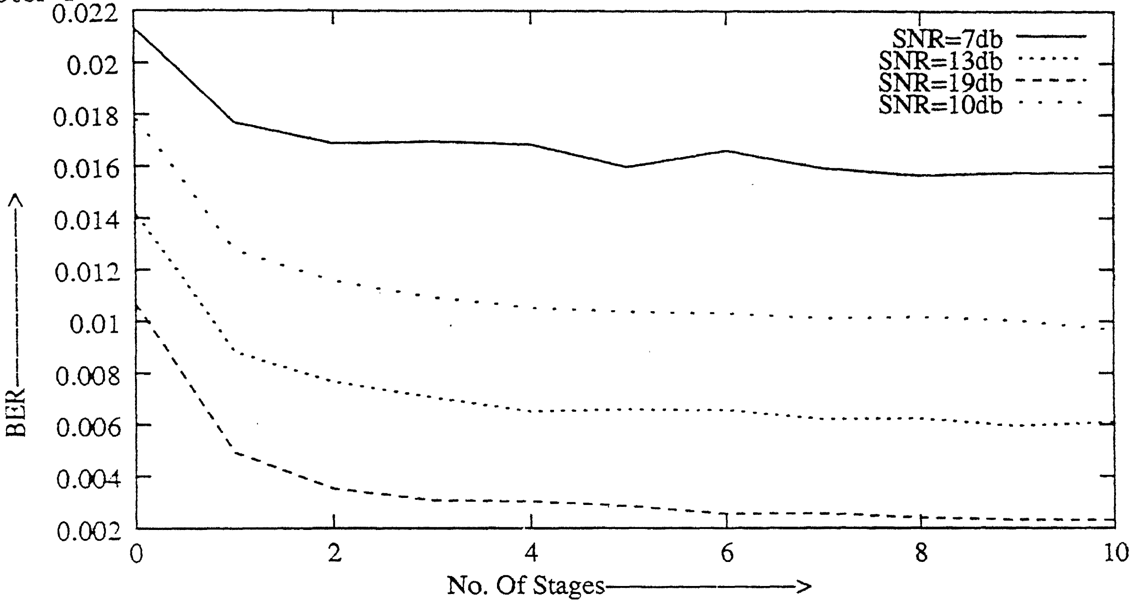


Figure 4.7: Curves for different SNR's in Gaussian channel using NDMD detection

4.5 Near-Far environment results

Finally the combined curves for the near-far environment are plotted for Gaussian and Rayleigh channel in Figures 4.20 and 4.21 respectively. Here first user is transmitting at 10db more power compared to all the other users. Even in this case also performance improvement is obtained compared to the conventional matched filter.

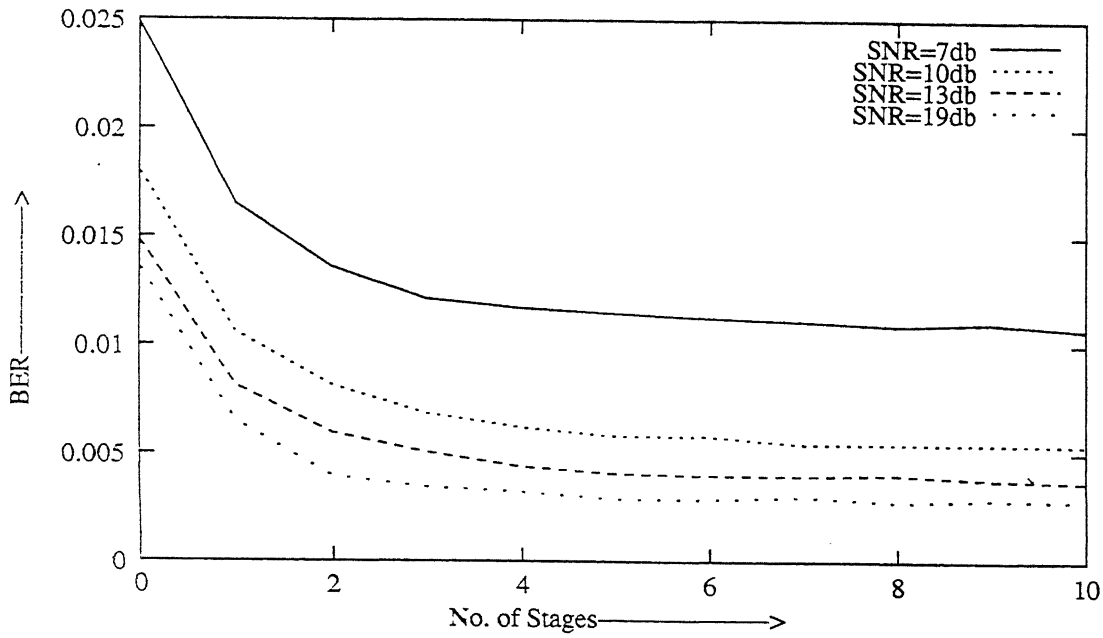


Figure 4.8: Curves for different SNR's in Gaussian channel using LPIC WCIE-detection

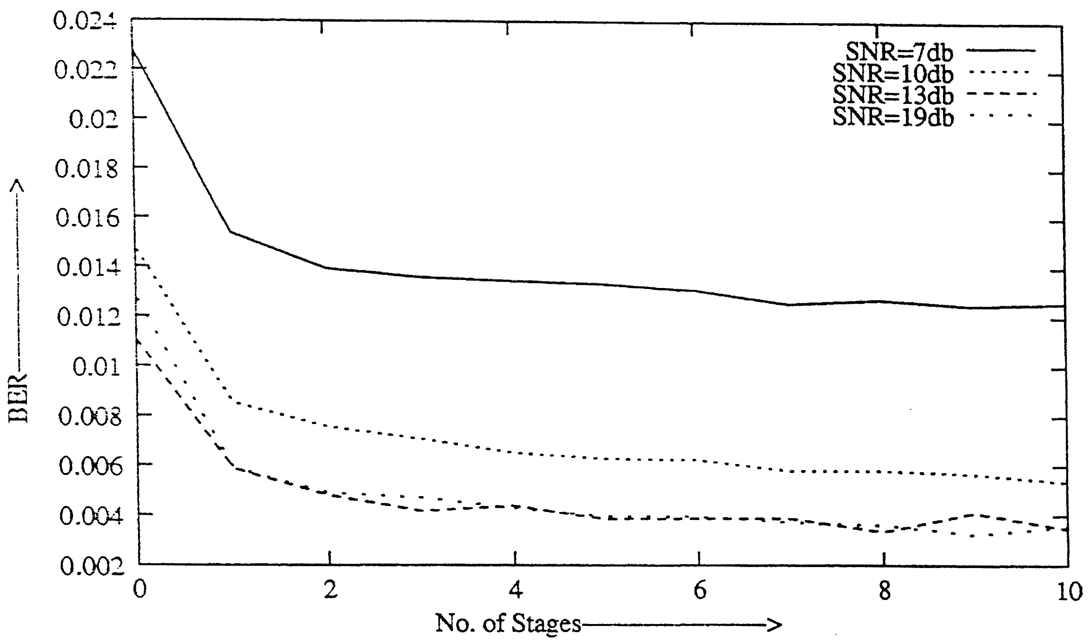


Figure 4.9: Curves for different SNR's in Gaussian channel using NDMD WCIE-detection

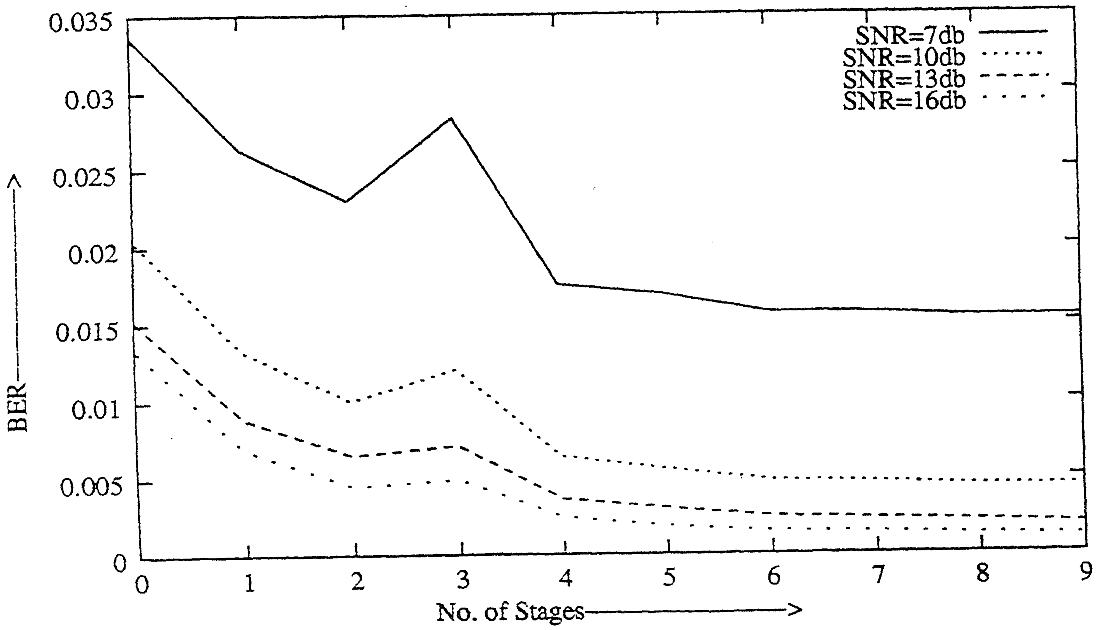


Figure 4.10: Curves for different SNR's in Gaussian channel using LPIC threshold-detection

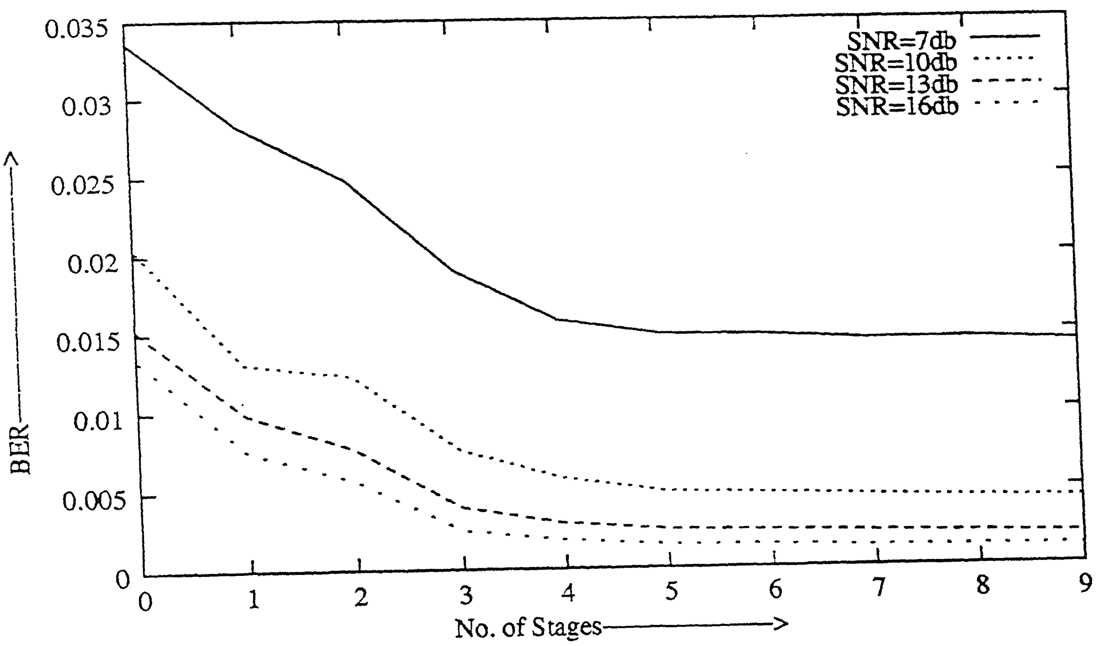


Figure 4.11: Curves for different SNR's in Gaussian channel using NDMD threshold-detection

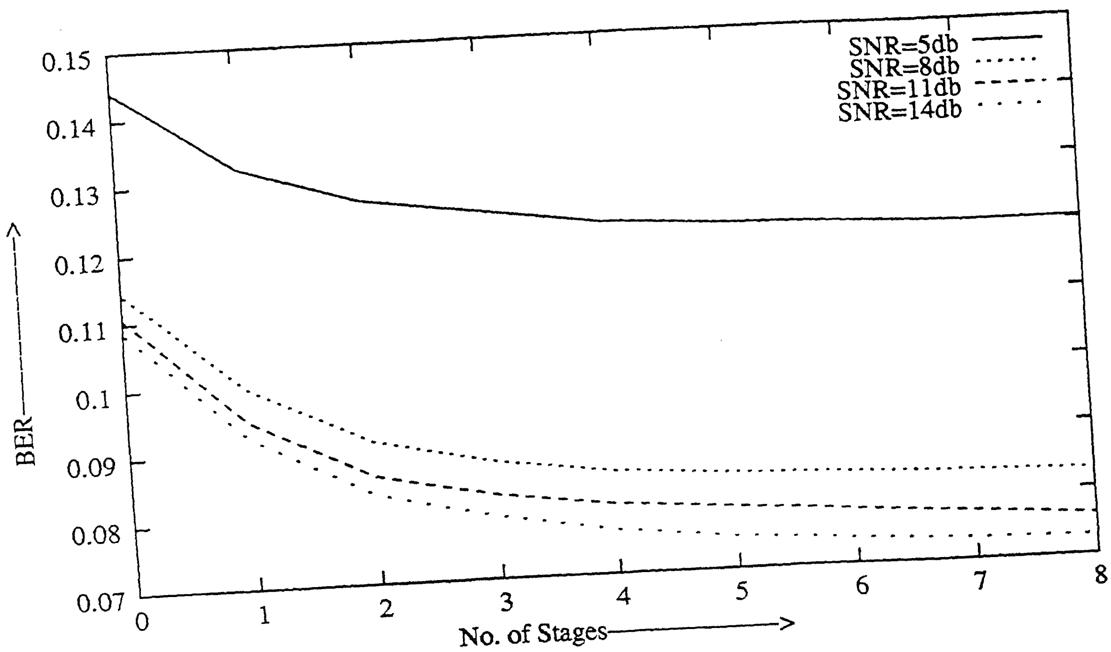


Figure 4.12: Curves for different SNR's in Rayleigh channel using LPIC WCIE-detection

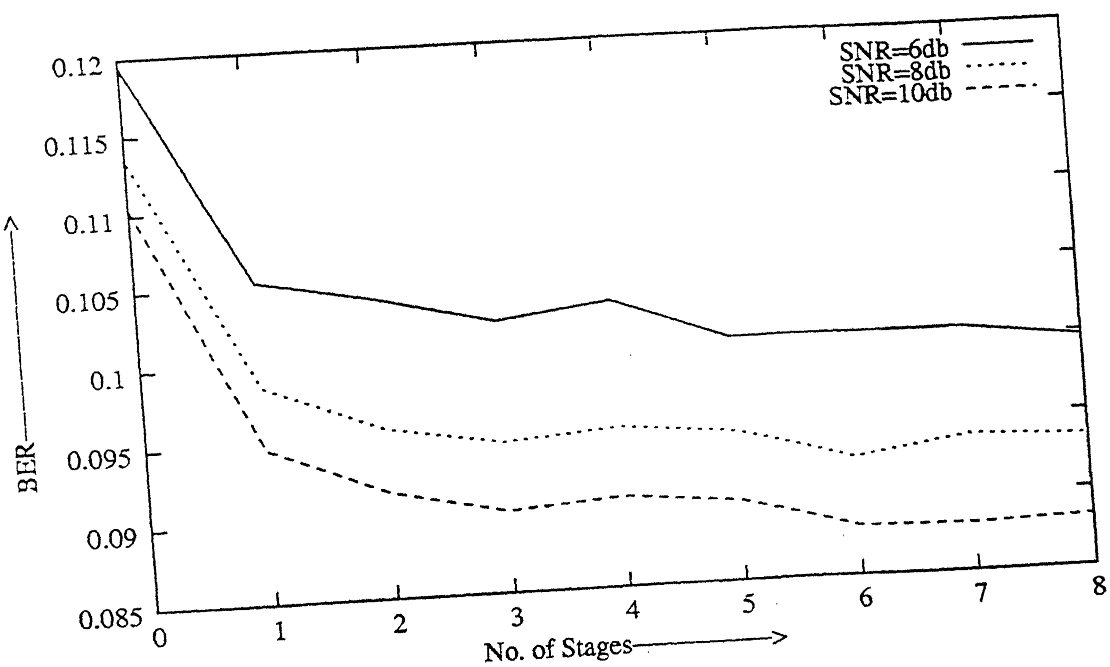


Figure 4.13: Curves for different SNR's in Rayleigh channel using NDMD WCIE-detection

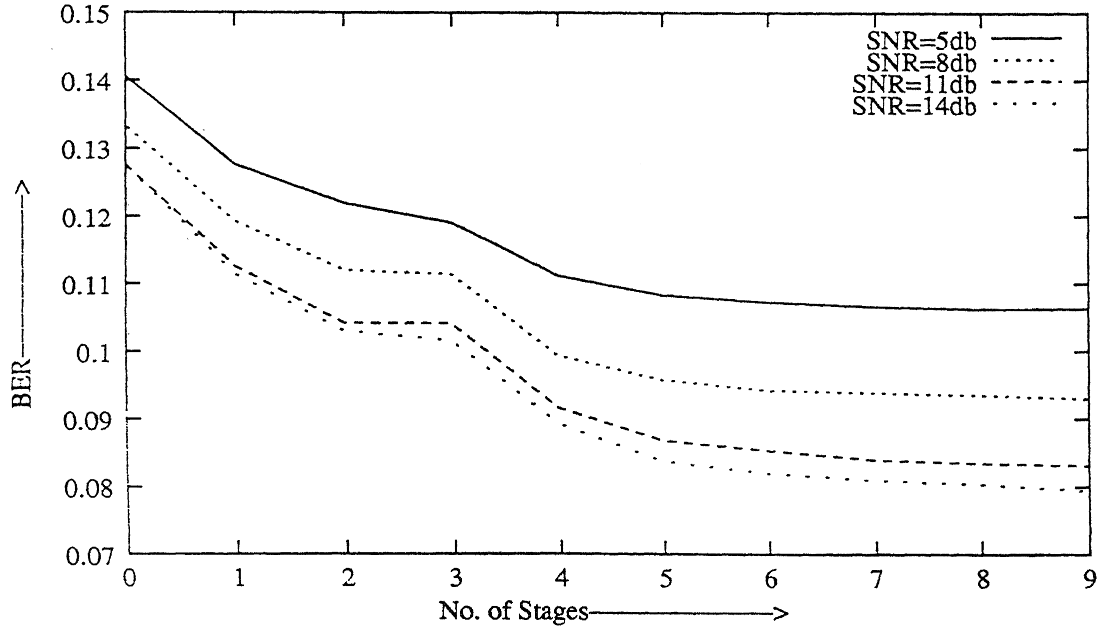


Figure 4.14: Curves for different SNR's in Rayleigh channel using LPIC threshold-detection

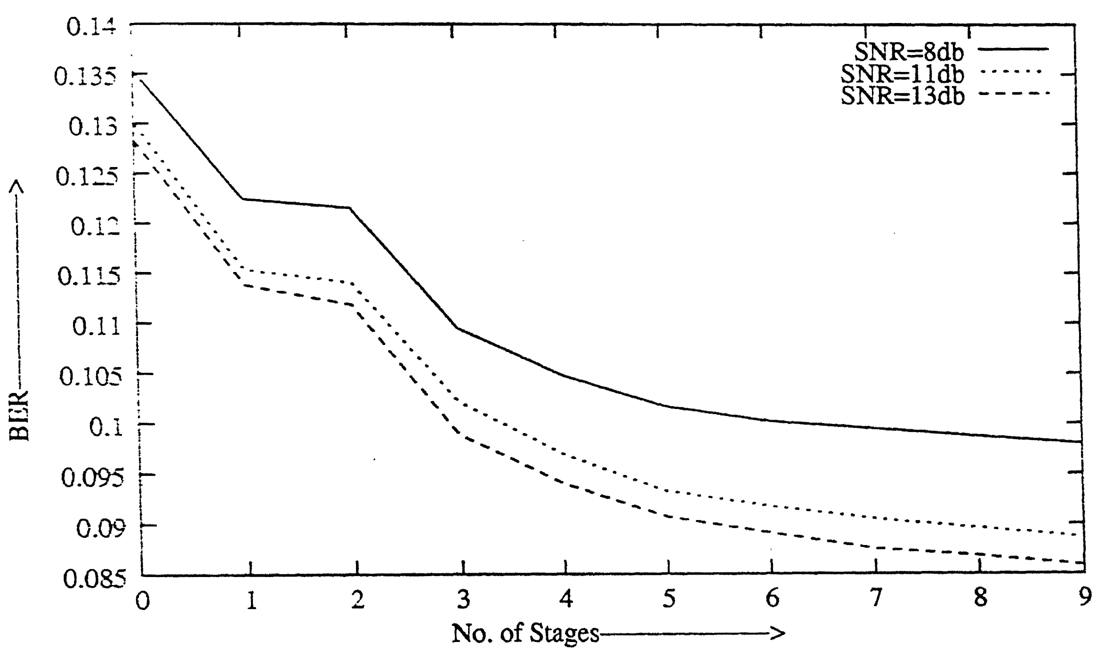


Figure 4.15: Curves for different SNR's in Rayleigh channel using NDMD threshold-detection

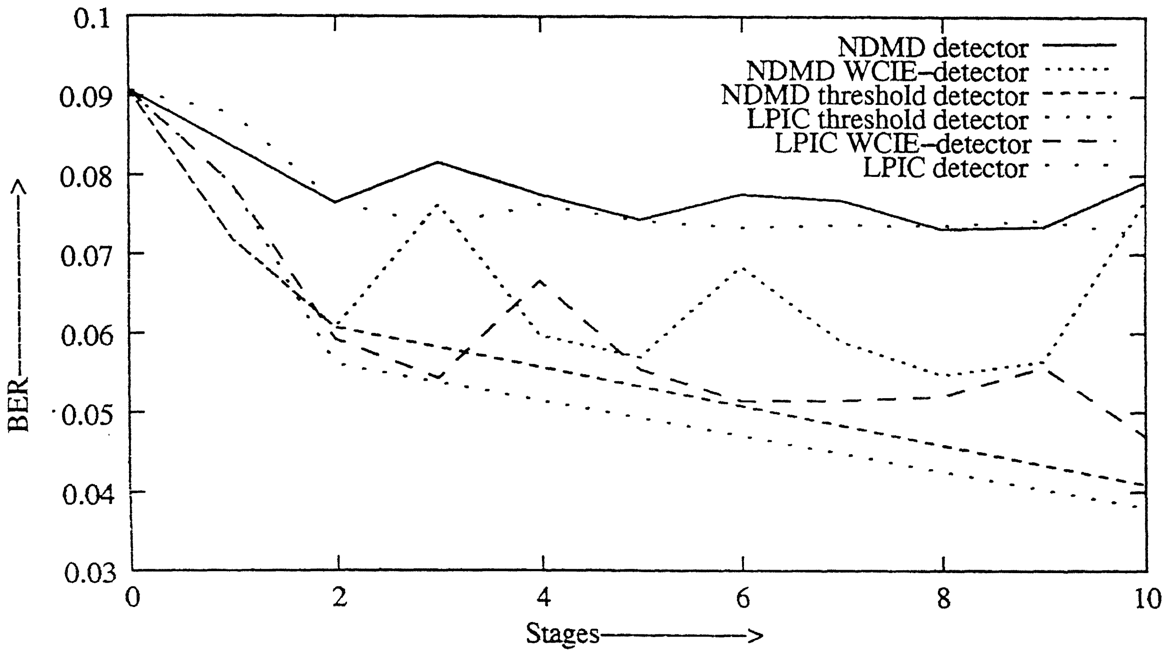


Figure 4.16: Curves for 14 users using different detectors in MAI channel

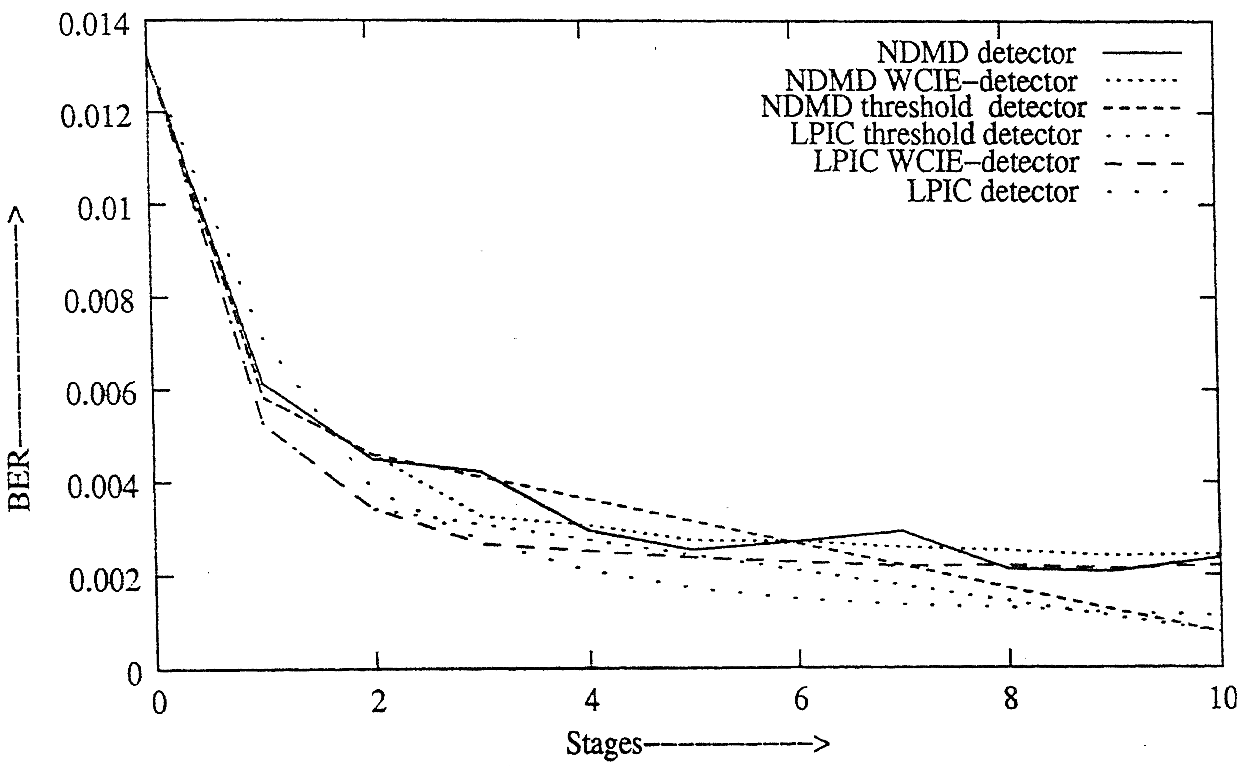


Figure 4.17: Curves for 10 users using different detectors in MAI channel

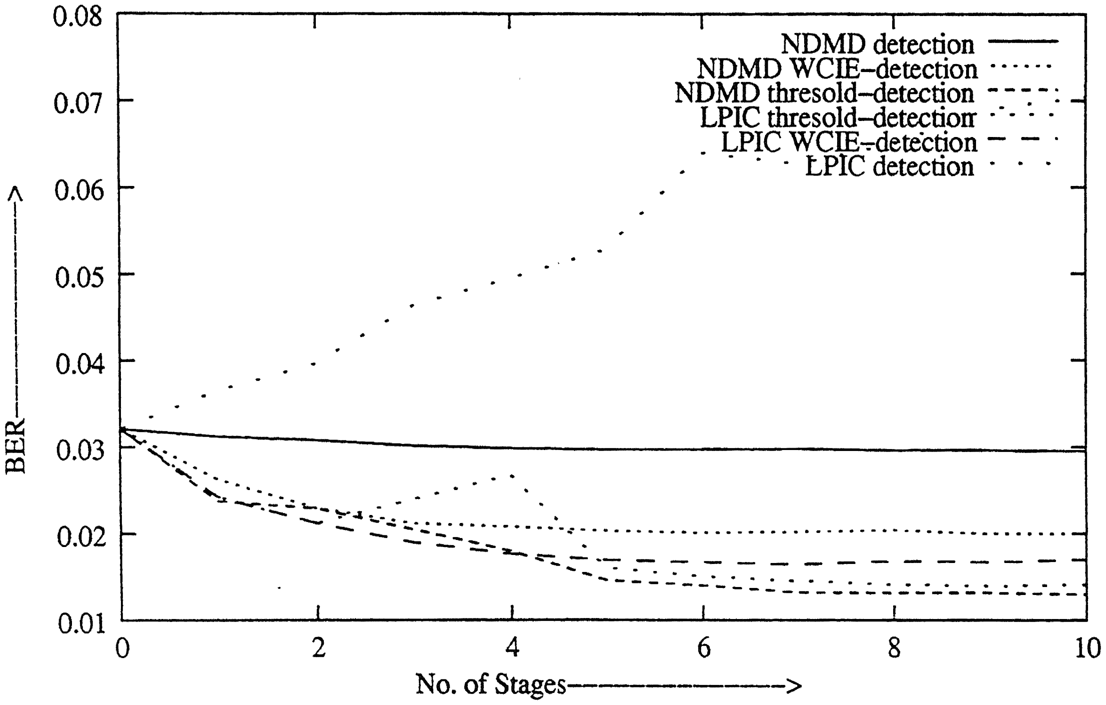


Figure 4.18: Curves for 10 users using different detectors in Gaussian channel. Here SNR=5db

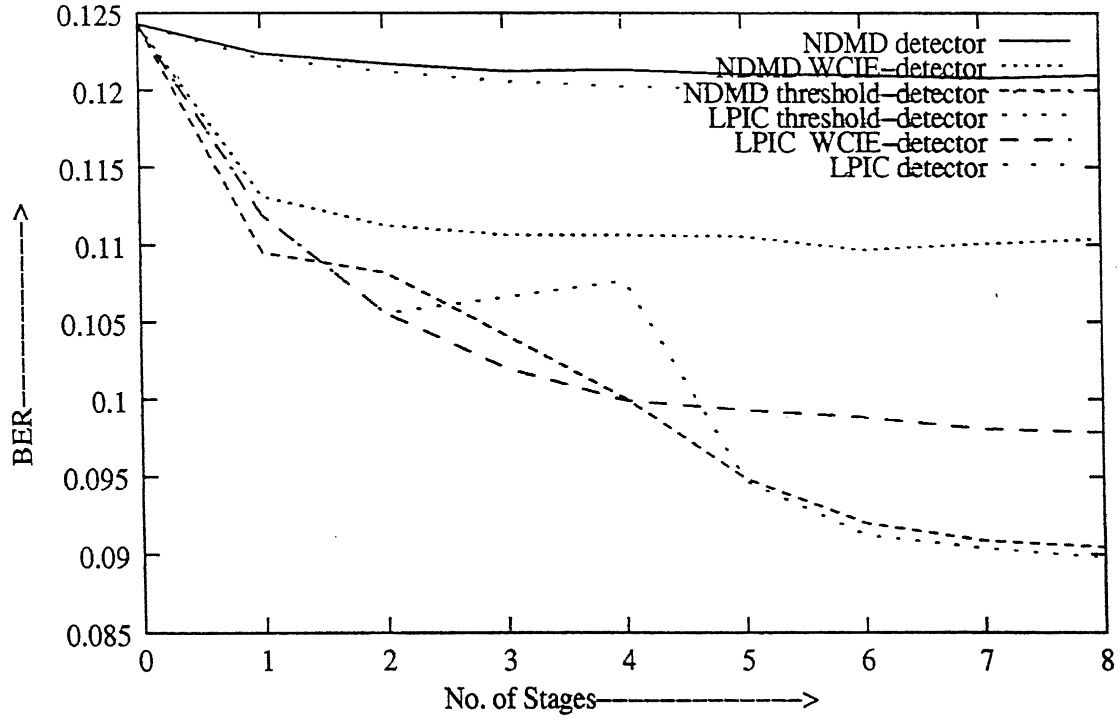


Figure 4.19: Curves for 10 users using different detectors in Rayleigh channel. Here SNR=5db

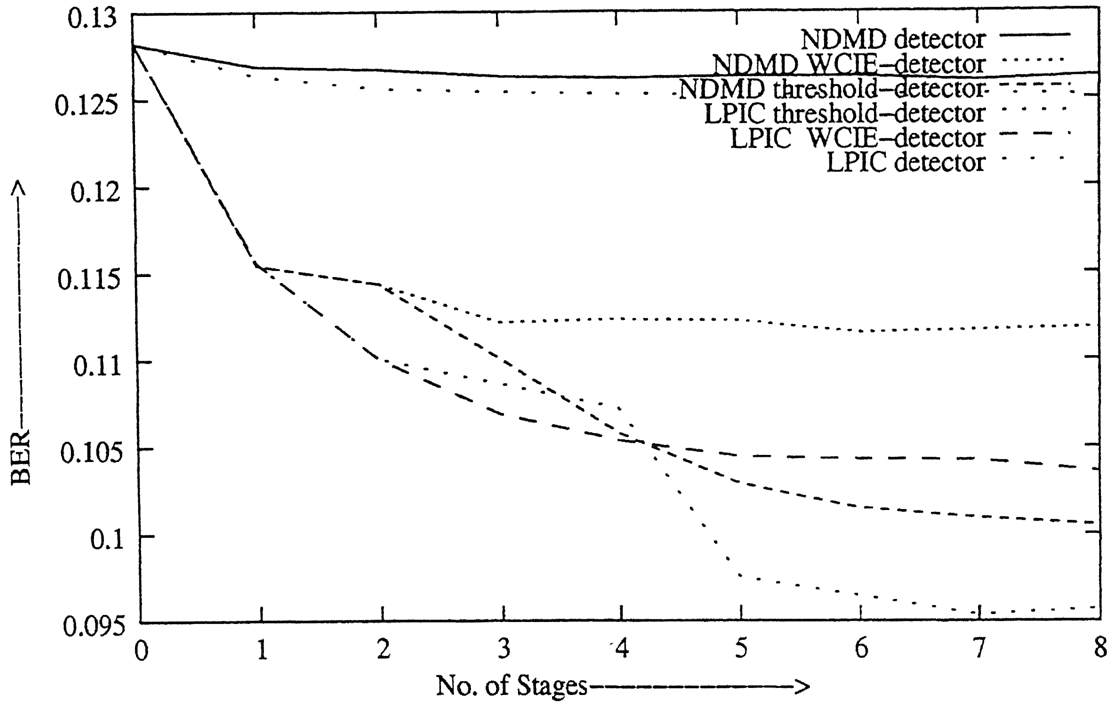


Figure 4.20: Curves for 10 users using different detectors in Gaussian channel with first user having 10db more power than other all 9 users. Here SNR=5db

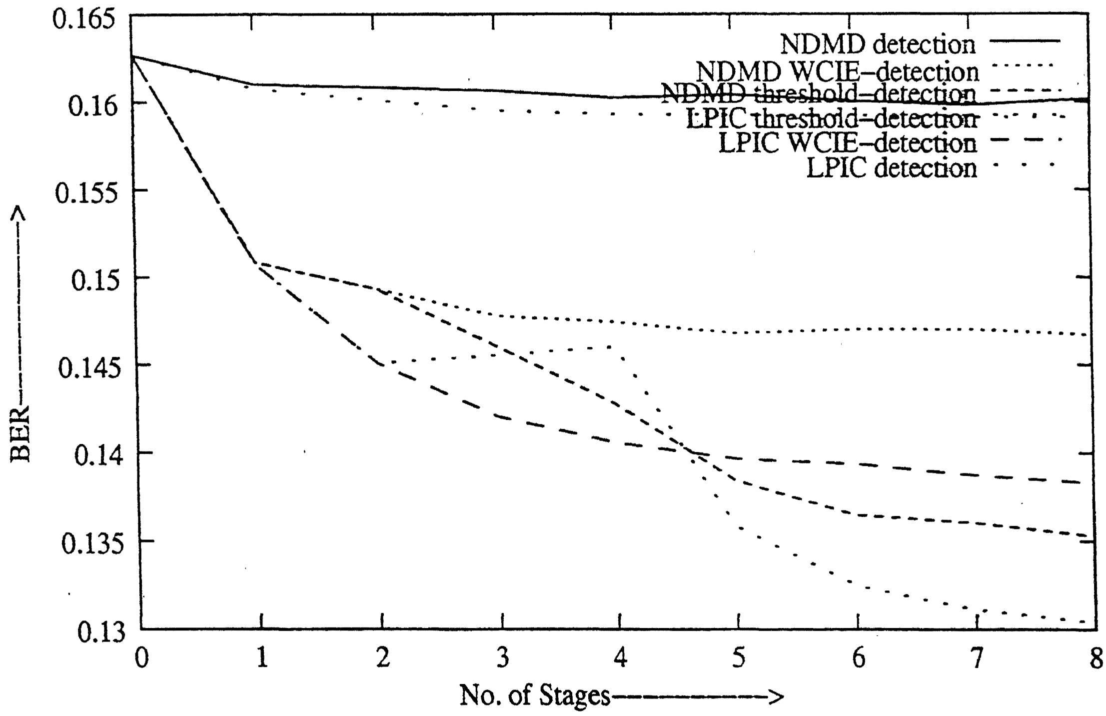


Figure 4.21: Curves for 10 users using different detectors in Rayleigh channel with first user having 10db more power than other all 9 users. Here SNR=6db

Chapter 5

Conclusions and Future Research

5.1 Conclusions

In this thesis multiuser detection techniques were implemented in the practical IS-95 systems reverse link by using simple iterative cancellation based multiuser detection techniques. Because of the large number of random variables involved, analytical approach is complicated and hecne simulation studies were done to obtain realistic results.

SIC and two recently proposed partial PIC techniques for the long code case were implemented for different channel conditions for different number of users in the system. The results show that improvement is obtained by employing multiuser detection but this improvement as compared to the BPSK/QPSK modulation results were less and to improve upon these results, two modifications were suggested in the original algorithms to suit the IS-95 reverse link envrionment. These modifications- WCIE-detection and threshold-detection- were implemented and results show still more improvement in the BER which enhances the capacity of the system. These modifications reduced the delay involved in the detection of the symbols though this is not a major problem in the reverse link. For the case of NDMD detection the weighting factor is same for all the stages and they are independent of the received signal strength of the user. Hence it is an attractive technique compared to the LPIC technique where the weighting factors vary from one stage to another and are shown to be dependent on the number of users and received signal strength of the users and they require continuous updation. These detection techniques provide improvement even when

near-far environment is prevalent in the system and hence are an attractive proposition to be considered for the next generation mobile systems as well to enhance the capacity of the present systems. Computational complexity of the detectors is also linearly proportional to the number of users. One important point to be noted is the uncoded system considered for simulation here. Hence all the results presented here will be suitably modified for a coded system resulting in more performance gains compared to the uncoded system.

5.2 Future Research

Future research can be directed in two directions. In improving the estimation of the detected bits which directly affects the calculation of MAI can be improved and secondly the amount of interference subtracted at each stage to get optimum results in the lowest possible number of stages. As increase in number of stages increases the complexity and hence delay, it is an important parameter for future research. The estimation of the transmitted symbol is normally done by hard decision. Performance improvement can be obtained if soft decisions are employed. Also the first stage in multiuser detection is normally the conventional match filter detector. This stage can be improved by employing non linear detection techniques to get better estimates for the next stage.

The other feature in which research can be done is the use of weighting factors for individual users. Each user can be assigned different weighting factor depending upon the estimation accuracy. Finally in the threshold detection the threshold can be varied from stage to stage to include the improved estimation at each stage interval.

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